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Investigating the impact of forested riparian areas on stream morphology in Iowa using aerial LiDAR

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Investigating the impact of forested riparian areas on stream morphology in Iowa using aerial LiDAR

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

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2019

DEDICATION

To Gizmo

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ABSTRACT

An ongoing disagreement in the fluvial geomorphology community deals with the impact forested riparian areas have on channel morphology. Despite the large amount of published studies on the benefits of riparian forests such as bank stability and reducing soil loss, some researchers suggest that reforesting floodplains increases the inputs of large wood (LW), which ultimately causes erosion, can decrease sediment storage, as well as promote channel widening. The majority of the research on the influence of riparian forests and LW on channel morphology has occurred on the coasts of the United States where streams are often steep and rough, the substrate is rock or coarse sediment, and the riparian areas are dominated by coniferous forests. The statistical power of the current research is also limited by small numbers of study reaches and watersheds and often focuses on smaller watersheds.

The purpose of this research was to explore the relationship between riparian vegetation and stream morphology in Iowa by amassing a large geospatial dataset characterizing channel width and riparian land cover across diverse physiographic regions of the state. To investigate whether streams running through forest were wider than streams running through riparian areas dominated by grass, pasture, or row-crops, a statistical relationship between riparian vegetation height and along-channel deviations in channel width was obtained using the Iowa LiDAR product for each. The results indicate that wider stream reaches are more likely to be surrounded by forest than narrow reaches, consistent with our hypothesis. Analysis of field observations from 10 forested stream reaches around the state was unable to clearly identify the cause of this relationship, but suggests that reaches with log jams are wider than those without. These results imply that conversion of riparian vegetation to forest could lead to channel widening, consistent with some previous studies. The field observations further highlight the need to better understand

the role of recruitment and persistence of large wood and log jams in the hydraulic geometry of alluvial channels.

CHAPTER 1: INTRODUCTION
1.1 Background

In the last decade, the number of river restoration projects has increased exponentially in order to enhance water quality, manage riparian zones, improve in-stream habitat, and bank stabilization (Bernhardt *et al.* 2005). It has been estimated that since 1990, $14 to $15 billion dollars has been spent on restoration efforts with an average of over $1 billion per year (Yochum 2018). A wide variety of approaches and goals exist when executing river restoration, but in a review of 37,099 stream restoration projects, the most common goals were water quality management, floodplain reconnection, flow modification, and riparian management (Bernhardt *et al.* 2005). With the median cost of these projects being $108,500, understanding and predicting the lateral movement of streams as well as any local external impacts that could potentially enhance or reduce stream widening are vital.

Alluvial channels are self-formed, adjusting their longitudinal and cross-sectional geometry to convey the water and sediment supplied to them. The dominant controls on the form of single-thread alluvial channels are the flow frequency and magnitude, size and characteristics of the bed and bank materials, valley slope, and bank vegetation (Hey 1978). These controls vary at different scales and their impact on a channel's geometry are difficult to isolate (Knighton 1984). Previous studies of altered hydrologic conditions have shown that cross-sectional form, specifically width, is the most variable factor of channel geometry (Knighton 1984). Assuming that discharge (Q) is the dominant independent variable causing spatial variation in width at the watershed scale, the relationship between width (w) and discharge can be modeled using the power-law function for width developed by Leopold and Maddock in 1953:

$$w = aQ^b$$

This width-discharge relationship is a component of a model framework referred to as hydraulic geometry, which describes conservation of mass in water flowing through an open channel cross-section. The empirical coefficients a and b are derived from a log-log regression of width and at-a-station or downstream discharge. At-a-station discharge is the variation in geometry of the wetted cross-section as discharge varies through time at a fixed location (Singh 2003). Downstream hydraulic geometry (DHG) utilizes a reference flow condition and presents spatial variation in channel form and process (Leopold *et al.* 1964). In areas where stream gauges are not available or bankfull stage is not apparent in the field, regional DHG curves are often created which relate width (w) to drainage area (A):

$$w = \alpha A^{\beta}$$

where α and β are empirical parameters that vary by region (Faustini *et al.* 2009). In an analysis of the average DHG for the U.S., the exponent β was reported to be 0.5 (Leopold and Maddock 1953). Even with the assumptions of constant A, variations in the basin will create scatter when DHG curves are plotted and most likely will differ from 0.5 (Leopold *et al.* 1964). DHG characterizes broad spatial patterns, but does not capture local variation or stochastic processes affecting channel width at the reach scale (Hession 2001, Anderson *et al.* 2004). However, DHG does vary across ecoregions as runoff processes and volumes vary (Faustini *et al.* 2009). For this reason, DHG regional curves are used primarily within a restricted geographic region with similar climate and geology as systematic changes in discharge and sediment are less likely to occur (Knighton 1984, Faustini *et al.* 2009). Once created, however, DHG regional curves can be used to make predictions of mean channel width and comparisons across regions. Recognizing deviations from stable alluvial channel width the nature and cause of with variation within regional curves is extremely important to river managers, geomorphologists, and engineers in achieving their restoration goals.

One of the most debated causes for local variations in cross-sectional form is riparian vegetation (Wolman 1955, Knighton 1984). Riparian vegetation is not only influenced by the hydrology and geomorphology of a stream, but in turn, the hydrology and geomorphology of the stream can be impacted by the vegetation. Previous studies on the topic have focused on the impact vegetation has on erosion and deposition of the system as well the migration of the channel, the density of the riparian vegetation, the inputs of large woody debris, and the scale of the stream, all in an attempt to better understand the relationship and prepare for stream restoration, channel designs, or policy modifications (Hey and Thorne 1986, Allmendinger *et al.* 1999, Faustini and Jones 2003, Olson *et al.* 2007).

Adequate vegetation cover and biomass provide stream banks protection during high streamflow periods and encourage the trapping and deposition of sediments for maintaining, rebuilding, or stabilizing stream banks (Schumm and Lichty 1963, Clary and Webster 1990). Deposition volumes and erosion rates vary with the type of riparian vegetation. In order to measure channel deposition and erosion, often channel width is used as a metric (Odgaard 1987, Allmendinger *et. al* 2005).

In a widely cited paper from 1986, researchers in the U.K. divided bank vegetation into types I-IV, which indicated the type and density of vegetation (grass or forest) (Hey and Thorne 1986). Not only did this study report bank vegetation as a major control of channel width, but in their analysis of 62 gravel-bed streams, they found grassy-bank streams to be 1.8 times the width of tree-lined streams (Hey and Thorne 1986). They inferred that tree roots stabilized banks and protected them from erosion and widening (Hey and Thorne 1986). Another U.K. study found bank erosion higher in moorland reaches due to pronounced bank undercutting (Stott 1997). Large roots (compared to smaller-shallow roots) can be more helpful in controlling the susceptibility of bank erosion and make forested cutbanks more difficult to erode (Charlton *et al.* 1978, Allmendinger *et al.* 2005).

In contrast, another widely-cited study in Wisconsin declared grassy stream reaches were narrower than forested reaches (Trimble 1997). In this study of four paired reaches, several physical stream variables were collected and compared in order to assess the effect that trees and grass had on channel characteristics. The author concluded that grassy reaches were narrower due to their ability to store more sediment as well as protect banks from erosion (Trimble 1997). The author also questioned public policies of planting riparian forests as the conversion from grassland or pasture to forest could cause a larger sediment flux while the vegetation change was occurring and the channel width was increasing (Trimble 1997).

In other similar studies, grassy reaches have been shown to be highly erodible (specifically bank undercutting), but the dense grasses cause deposition that counteract the erosion causing narrow channels that can rapidly migrate (Allmendinger *et al.* 2005). Likewise, forested reaches have low erodibility (due to armoring by tree roots), but due to their low accumulation rates on point bars, wider, slowly migrating channels are formed (Davies-Colley 1997, Hession *et al.* 2003, Allmendinger *et al.* 2005).

Trimble 1997 also cited large woody debris as a likely cause for destabilizing stream banks by diverting stream flow into banks and causing bank erosion and widening in the forested reaches (Trimble 1997, Figure 1).

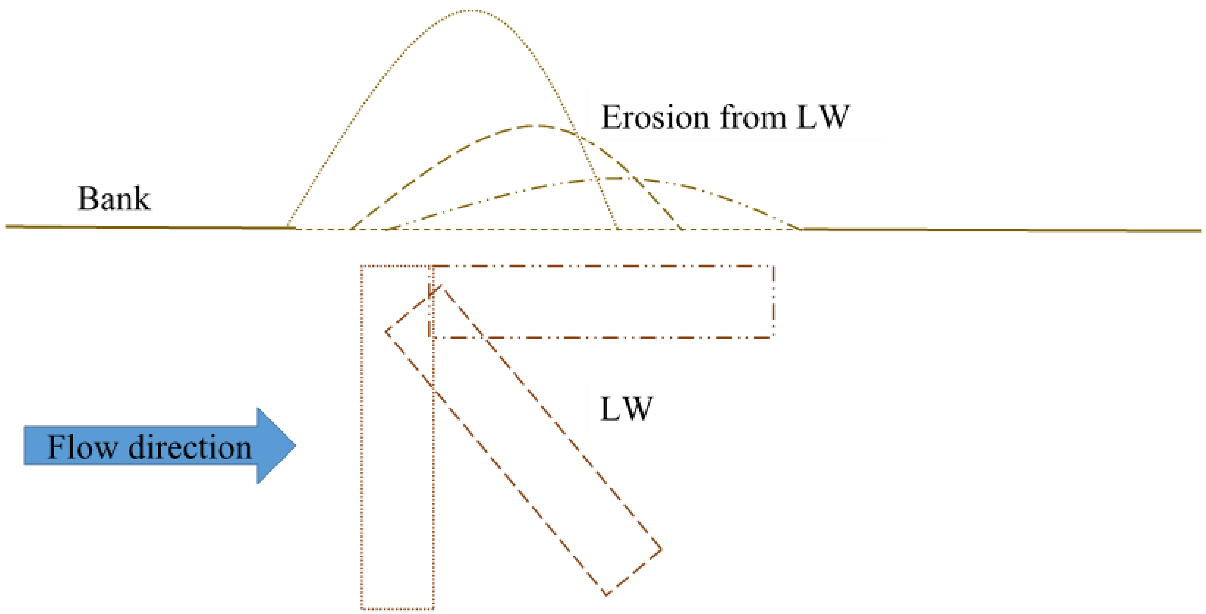

Figure 1: Diagram of LW orientations in stream channel and their resulting bank erosion.

Large woody debris (LWD) or simply large wood (LW) refers to a tree piece at least 10 cm in diameter and 1 m in length which has entered the active channel or floodplain (Gurnell 2002, Wohl 2017). Depending on the region, the recruitment mechanisms of LW into streams differs, but common causes of recruitment can be individual tree mortality, mass tree mortalities (e.g., from storms, insect outbreak, or fire), beavers, hillslope instability, or bank erosion (Moore and Richardson 2012). The size of the LW entering the stream is controlled by the tree species, age, size, and management history (Gurnell 2002). Once within the stream, LW can have an impact on the flow hydraulics of the stream, providing roughness to the stream either as an individual piece or within a wood accumulation or "jam" (Gurnell 2002). Studies in New England have documented stream widening, avulsions, and meandering due to LW dams and fallen trees (Zimmerman *et al.* 1967). LW jams have also been shown to decrease stream velocity and discharge by affecting flow routing and by increasing sediment storage, dissipating potential stream energy, and impacting the frequency of overbank flows (Zimmerman *et al.* 1967, Aumen *et al.* 1990,).

Channel width is a key factor controlling the dynamics and the morphological effects of LW in streams (Nakamura and Swanson 1993, 1994). Gurnell *et al.* 2002 developed a size classification for channels in regards to how they would interact with LW:

Table 1: Size classes of streams developed by Gurnell et al. 2002. Based on the ratio of typical tree height to river width.

Small	Width less than the majority of wood pieces
Medium	Widths greater than the size of most wood pieces
Large	Channels are wider than the length of all of the wood pieces delivered to them

The size of a stream greatly impacts wood retention and the frequency of jams. In large streams, LW are most likely mobile (Gurnell 2002). In a small stream, LW is likely to be retained due to the lack of stream velocity to move it. In a medium stream, LW is likely to move and accumulate behind key pieces to create jams. In Iowa, the typical height of riparian trees ranges from 10-30m. In some states, LW is removed from streams in order to improve navigation, eliminate hazards to infrastructure like bridges, and to control erosion (Shields and Gippel 1995).

Due to perceived negative impacts of forested riparian areas, some, like Trimble 1997, would caution against the promotion of trees in riparian conservation programs over grass. Alternatively, other geomorphologists and stream ecologists would argue in favor of the use of riparian trees as forested reaches contain more macroinvertebrates, processing of organic matter, and nitrogen uptake due to the wider, more natural stream shape (Sweeney *et al.* 2004). Forested reaches also contain more LW which has many documented positive impacts like enhancing habitat abundance and diversity by influencing and creating more local diversity of flow velocity, depth, and erosion and deposition along the bed and banks for microbes, invertebrates, and fish (Shields and Gippel 1995, Chen *et al.* 2008, Wohl 2017,). LW jams also reduce flow velocity and enhance resource availability for pioneering vegetation (Naiman *et al.* 2005). Jams also have the ability to create backwaters and eddies that allow for the deposition of sediment and organic matter. If there is considerable disagreement in the geomorphology and engineering community on how forested riparian area impact channel width, we should be concerned about policies being created, utilized, and set by our government within these areas.

So far the impact forest has on channel width has been studied on a relatively small scale:

Table 2: Overview of commonly cited studies and their location and number of reaches.

Study	Location	Total channel length (km)	# Reaches
Zimmerman *et al.* 1967	Northeast Vermont	~ 1.60	5
Trimble 1997	Southwest Wisconsin	20.0 (?)	4
Davies-Colley 1997	New Zealand	2.0	20
Sweeney *et al.* 2004	Eastern Pennsylvania	~1.6-3.0	16
Hession *et al.* 2003	Eastern Pennsylvania	~2.6-5.2	26

Of these widely cited papers, the majority investigated streams with drainage areas < 50 km^2 and with reaches rarely exceeding 100 m in length (Davies-Colley 1997, Hession *et al.* 2003, Sweeney *et al.* 2004). Although these studies have been vital in investigating the important questions pertaining to the impact riparian vegetation has, claims made by these research efforts lack significant statistical power. Some have approached the issue by evaluating larger published data sets, but ultimately cannot capture the processes controlling width and acknowledge the importance of site specific data (Anderson *et al*. 2004, Faustini *et al.* 2009).

As many indicate LW as an impact on channel width, research on LW also has some limitations. The majority of the in-depth research on LW and its morphological and ecological influences take place within undeveloped mountainous regions like the Front Range of Colorado, Italy, Chile, and the Pacific Northwest (Wohl 2017). Areas like Maine and the Pacific Northwest often generate LW research due to the prevalence (or unfortunate absence) of salmon (Magilligan *et al.* 2008). Many of these studies also have developed methods of quantifying wood volumes which are specific to their tree types, which often are conifers. Although current LW data is informative, it has been acknowledged that there is relatively little known about LW in large rivers (>500 km2) and the central United States (Wohl 2017).

Overall *very* few studies on the relationship between riparian vegetation and stream morphology have taken place in the Midwest (Trimble 1997, Martin *et al.* 2016, Figure 2).

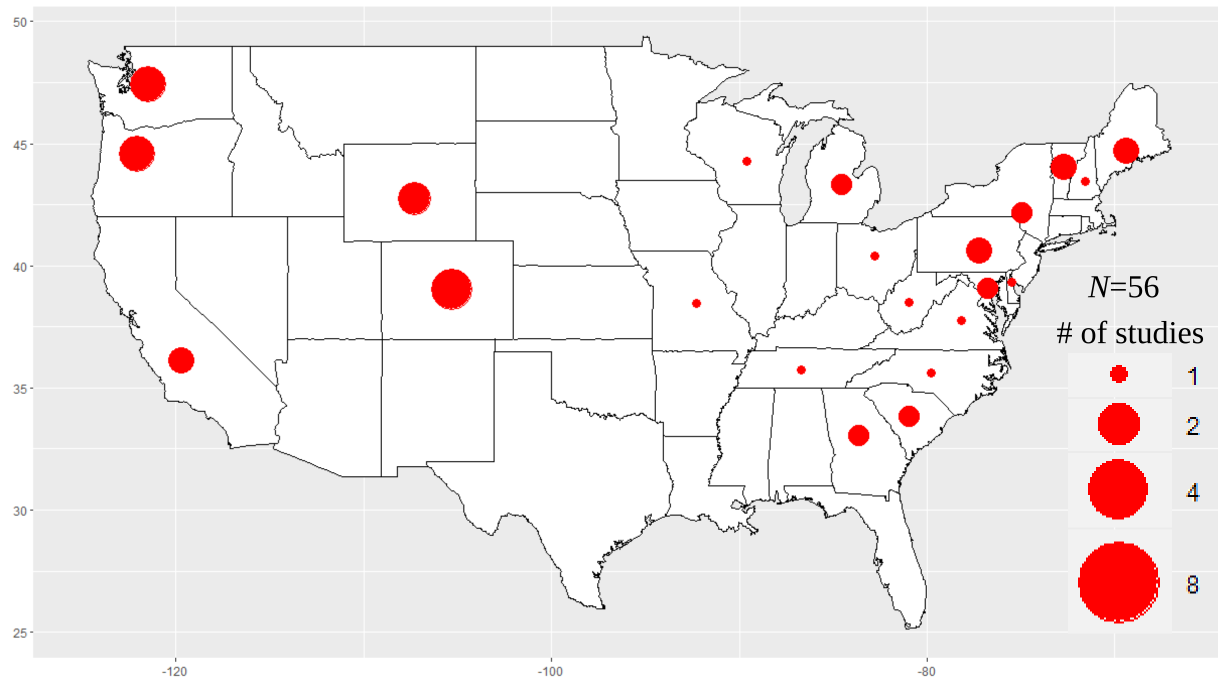

Figure 2: Diagram of studies pertaining to riparian vegetation and channel morphology. Size of circle represents number of studies. Notice the lack of studies in the Midwest as well as the Arid West.

It is risky to apply the results from past studies to the agriculturally dominated watersheds of the Midwest. The highly modified streams have suffered from very different disturbances (e.g., straightening and agricultural tile drainage networks) than those common to the Pacific Northwest. Streams in the Midwest typically have lower-gradients finer streambed sediments and finer and more cohesive bank material, where often other studies have inspected cobble bed or bedrock constrained rivers (Wohl 2017). Forest is also not as widespread in Midwestern uplands and is dominated where it is present by hardwood deciduous forests. The extent of these forests has been highly modified since European settlement (Mutel 2008). Applying the conclusions about riparian vegetation from the current studies to states like Iowa, Nebraska, and Illinois could be inappropriate.

Furthermore in the Midwest, knowing the potential outcome the riparian vegetation type has on the erodibility of the channel banks, as well as its ability to slow and store sediment, is vital. The Upper Mississippi River Basin drains freshwater with extremely high levels of excess nutrients, particularly phosphorous and nitrogen, to the Gulf of Mexico and has contributed to its ongoing issue of eutrophication and hypoxia (NOAA 2017). Runoff from the uplands of watersheds can be a source of excess nutrients as well as erosion. Published literature cites streambank erosion and failure, as well as gully erosion, to account for 7–92% of the suspended sediment load within a channel and 6–93% of total P (Fox *et al.* 2016). In 2001, the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force was created, which since then, has held states accountable for their nutrient contributions and their subsequent mitigation and monitoring (EPA 2017). If states are attempting to reduce their nutrient loads, limiting erosion is imperative.

The purpose of this research was to investigate the impact riparian vegetation has on channel width in the state of Iowa. Not only was this the first research of its kind in Iowa, it also was unique in that it utilized remote sensing to analyze channel morphology across an entire state. There are two questions we hoped this research could answer:

1. In Iowa, are streams running through forest wider than streams running through grass?
2. If streams are wider through forest, is the hydraulic impact of LW the mechanism making them wider?

In order to answer these questions, a mix of geospatial and field methods was used to analyze streams of a wide variety of drainage areas all across the state to create a robust data set. The geospatial methods created for this project allowed for streams and their adjacent riparian areas anywhere (no matter public or private) to be analyzed, free of charge to the user. Methods also could be used on wadable or nonwadable complex river segments of all sizes and shapes. This distinctive data collection process allowed for the localized collection of riparian vegetation while also gaining big picture conclusions about the entire state of Iowa. With this research, we hope to fill the gap of research in the Midwest investigating the impact riparian forests have on stream morphology and the mechanisms driving possible widening, as well as make conclusions and recommendations to reduce erosion.

CHAPTER 2: METHODS
2.1 Geospatial Methods

Several streams were chosen within the state of Iowa for this research. Recognizing the diversity of physiography and land-cover regimes across the state, Iowa has been divided into several different landform regions (Prior 1991, Figure 3).

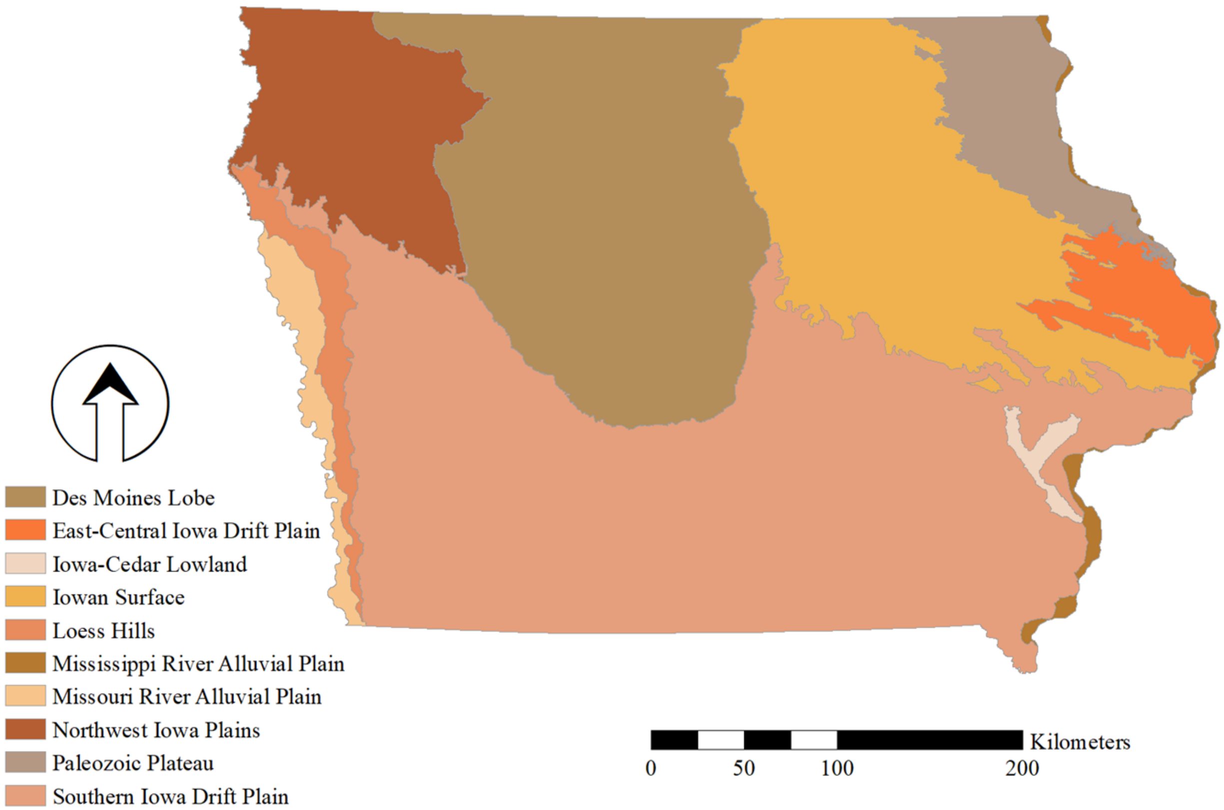

Figure 3: Landform regions of Iowa. The Des Moines Lobe is the most recently glaciated; only 12,000-14,000 years ago (Prior 2017).

The time elapsed since glaciation has affected regions differently and caused the soil parent material, bedrock, elevation, slope, and groundwater interactions to be different across these landform regions. The geologic differences between the Iowa landforms can be quite noticeable. For example, the watersheds existing in the northeast corner of the state within the Paleozoic Plateau contain more dramatic slopes within their catchments compared with the watersheds on the Des Moines Lobe (Figure 4). This reflects the difference between ages of the landform regions and the geomorphic processes which have been able to shape the Paleozoic Plateau for hundreds of thousands or more years than the geologically-young Des Moines Lobe landscape. The areas in northeast Iowa also contain karst, which allows streams to interact with groundwater springs. Another example is the Loess Hills of western Iowa. The wind-blown soils originate from the Missouri River and are thicker in this western-border region than anywhere else in the state. Due to their silty composition, the soils are eroded extremely easily and impact turbidity, channel-bottom composition, and floodplain development in the catchments. Along with controlling soils and topography, these geologic differences govern stream evolution, migration patterns, and the vegetation which grows (and is planted) within the landform.

The vegetation within the landform regions has been greatly impacted by humans due to the high organic content in the soils and success of farming. Prior to the arrival of white

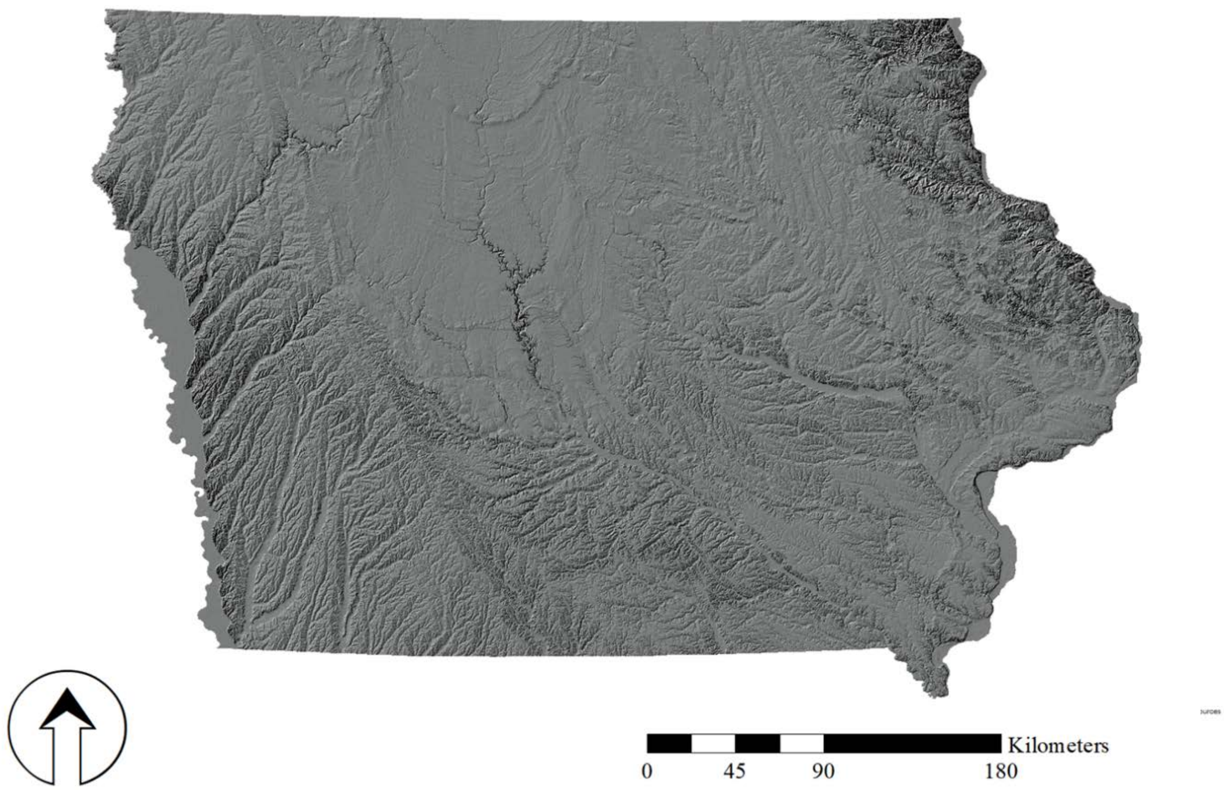

Figure 4: 30m hillshade of the state of Iowa. Darker grey represents steeper slopes. Source: Iowa DNR GeoData.

settlers,prairie was the dominant vegetation across the state (Van Der Linden and Farrar 1984). Trees also existed within this landscape, but were mostly restricted to stream valleys and their tributaries and surrounding natural lakes (Figure 5). Within Figure 5, as the stream order increases, the percentage of forest within riparian areas increases, while prairie decreases (Figure 6). In total,

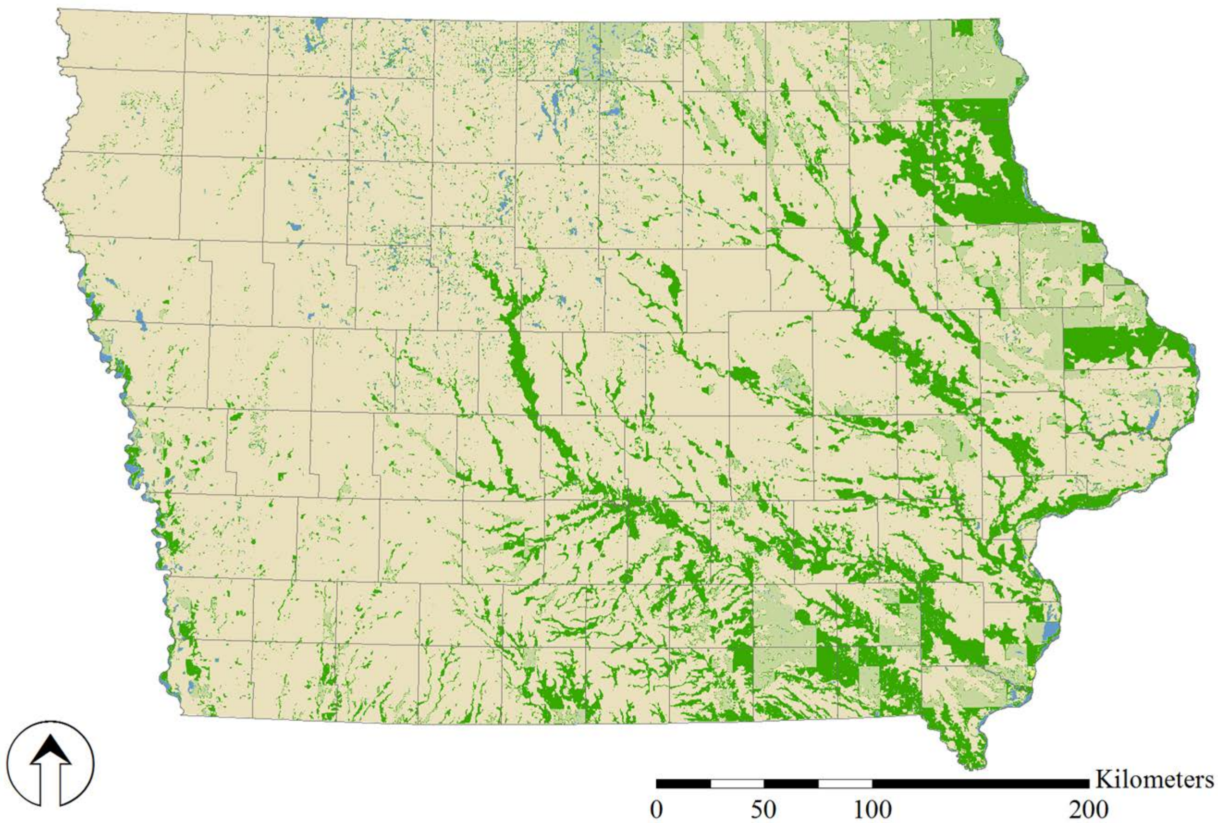

Figure 5: Historical vegetation of Iowa, 1832-1859. Forested areas (green) largely existed in riparian areas. Source: Iowa DNR GeoData

approximately 18% of Iowa was forested at the time of settlement (Van Der Linden and Farrar 1984). The virgin floodplain forests of Iowa contained elm, ash, and walnut. Oak, hickory, and basswood were found on the adjacent slopes (Aikman and Hayden 1938).

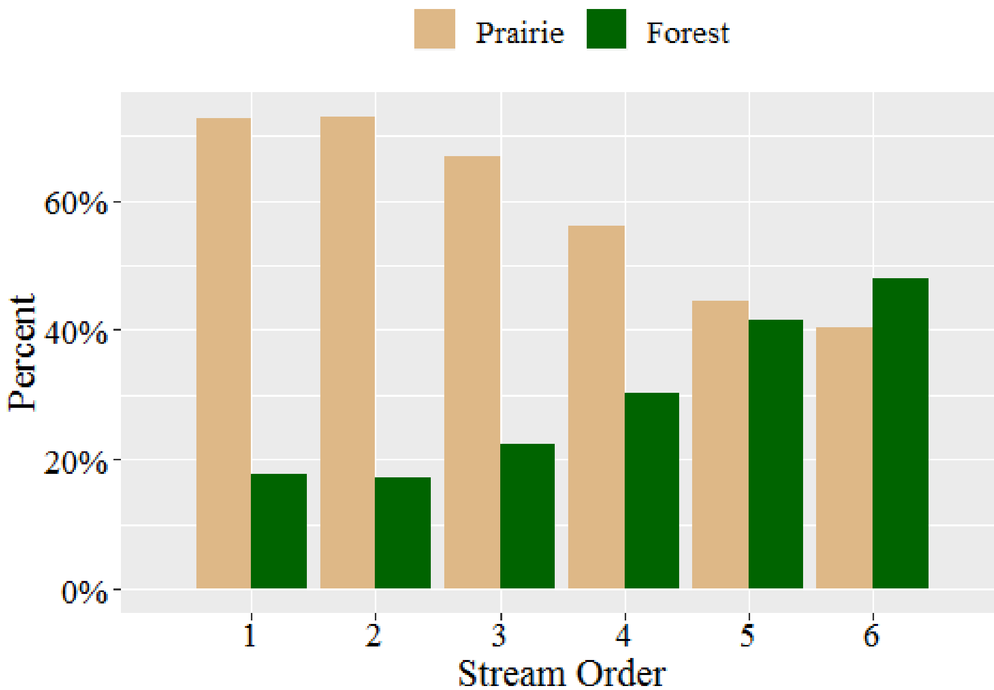

Figure 6: Percent of historical prairie and forest by stream order. Stream order increases to the right.

As wildfire was suppressed by settlers, trees were able to extend their habitats in some parts of the state. Within the eastern and southeastern parts of Iowa, the trees that managed to survive in locations not adjacent to water were removed for timber or to farm the land. In western Iowa, the limited trees in constricted stream valleys were also cleared for farming or depleted for logs, lumber, and wood supplies (Aikman and Hayden 1938). Today, forest still primarily exists in the floodplains and slopes of narrow stream valleys in Iowa (Figure 7). Prairie, however, is now extremely rare in Iowa. In 2017, according to the United States Department of Agriculture's Statistics Service, 36.7% of the land cover in Iowa was corn, 27.17% soybeans, and 14.1% grass and pasture. Only 8.63% of Iowa contained deciduous forest (CLD 2017).

In order to maintain as much land in agriculture as possible, extensive ditch and drainage systems were installed in Iowa in the early 1900s, which eventually led to water rapidly entering streams while sediment from the uplands decreased due to soil conservation programs across the state (Tomer *et al.* 2005, Blann *et al.* 2009). The response from the streams has been to incise, creating deep and confined channels with tall floodplain banks.

The evolution of channels over time is often characterized using the widely-cited channel evolution model (CEM) developed by Hupp and Simon (Simon 1989). In the model, there are six stages of channel evolution for alluvial channels disturbed by systematic land-use changes altering the balance of sediment and discharge (Simon and Rinaldi 2006). When the stages are applied to Iowa, Stage I is a natural stable channel before any anthropogenic influences. Disturbances caused by humans by altering the hydraulic and sediment regime for agriculture result in Stage II. Stage III is the response from the modifications resulting in channel incision: a declining channel bed and taller banks, but still stable. When the banks exceed the threshold for mechanical stability, bank failure leads to channel widening in Stage IV. Stage V is reached when incision is surpassed by sediment inputs to the channel widening and bank failures and aggradation occurs. Stage VI is the establishment of a new stable channel built within the degraded trench of the former channel (Simon 1989). The majority of Iowa's streams are currently characterized by Stage III and IV.

Due to the differences in the CEM, geology and land cover, and their potential resulting impact on channel geometry, I attempted to choose several watersheds and stream reaches within each of the major landform regions (Figure 8, Table 3). The state of Iowa was treated as the region when creating regional DHG curves as we wanted our results to be representative of the whole state and not be specific to any one landform region or allow certain characteristics of a landform region to bias or control the end results. Certain limitations did exist when choosing sites which will be discussed in further detail in following sections.

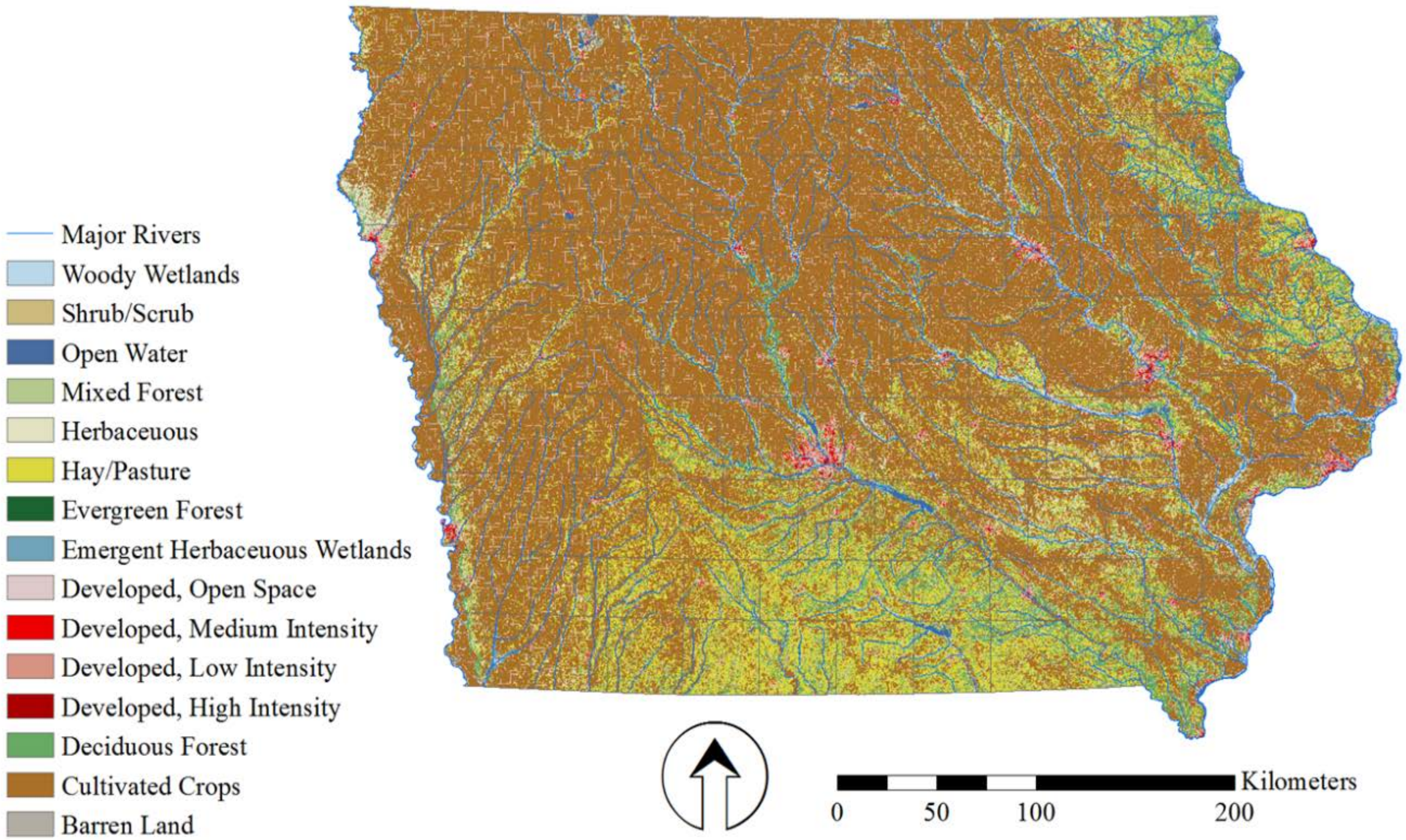

Figure 7: National Land Cover Dataset of 2011 created from reclassifying aerial imagery. Major rivers overlaid to show riparian corridors. Source: NLCD 2011 and Iowa Geodata.

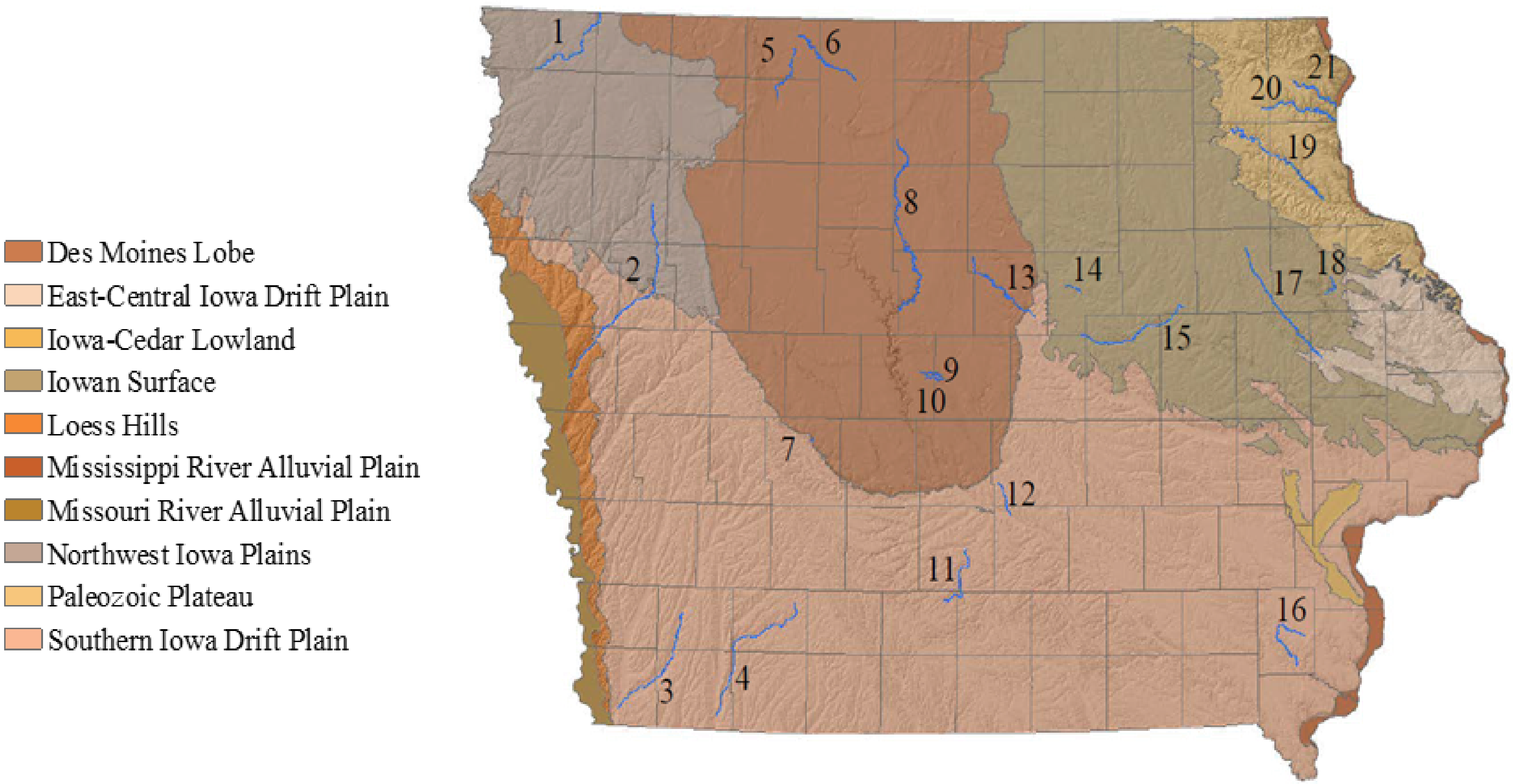

Figure 8: 21 streams included in geospatial analysis. Table 3 contains names and drainage areas of all streams. Blue line is stream centerline. Source: Iowa Geodata

Table 3: Streams with identifying number seen in Figure 5. Identifying numbers in bold were visited in the field. Drainage area values from Iowa DNR and USGS.

Identifying #	**Stream**	**Drainage area (km^2)**
1	Little Rock River	1192
2	Maple River	1920
3	Lower East Nishnabotna River	681
4	East Nodaway River	864
5	Jack Creek	292
6	Prairie Creek	252
7	Springbrook Creek	< 10
8	Boone River	2346
9	Onion Creek	51
10	Otter Creek	438
11	Clear Creek	< 20
12	Walnut Creek	52
13	South Fork Iowa River	570
14	Holland Creek	57
15	Wolf Creek	861
16	Big Creek	425
17	Buffalo Creek	598
18	Plum Creek	61
19	Turkey River	4361
20	Yellow River	627
21	Paint Creek	221

2.2 Geospatial Data Collection Methods

Geographic information systems (GIS) were extensively used in this project as they allowed for mass data to be collected from watersheds of varying sizes and locations all across the state. All the data utilized were freely available through the federal or state government. All image processing and geospatial analyses were performed in ArcGIS 10.5 in the NAD 1983 UTM Zone 15N Projection and NAVD88 vertical datum.

The majority of the geospatial methods for this project utilized the statewide aerial LiDAR products flown between 2007-2010 in Iowa. Light Detection and Ranging or LiDAR is a type of active remote sensing technology that is widely used to quickly and accurately measure elevations and vegetation characteristics. Using the LiDAR products, the Iowa Department of Natural Resources (DNR) digitized stream banks across the state; pending the stream was greater than 7 m wide (personal communication with C. Wolter and B. Gelder 2017). The use of DEMs derived from LiDAR point clouds to delineate channel banks does have limitations. When flying LiDAR, water absorbs the infrared signals and appears flat in the resulting DEMs. The extent of the water in a DEM would represent the wetted width of the channel at the time the LiDAR was shot and not the bankfull width. In order to overcome this issue, the surrounding banks were digitized by DNR staff and these data are used in this study. By simply using the top of banks, the width derived from GIS will only be an approximation of the channel width and not the bankfull width, which in Iowa would typically require on-site examination.

The Iowa DNR also digitized stream centerlines using similar methods, however, all stream centerlines were digitized no matter the size of channel. With these shapefiles, it was possible to have the left and right banks and the centerline for many streams in Iowa. Similar studies have utilized LiDAR to delineate stream banks and evaluate stream morphology (Kasprak *et. al* 2011, 2012, Sofia *et. al* 2015).

The process of choosing watersheds for analyses began by overlaying the bank and centerline, state counties, landform regions, and the Hydrologic Unit Code (HUC) 10 watershed shapefiles. HUC 10 watersheds were chosen due their prevalence in Iowa as well as their likelihood of being a medium stream using the channel rating mentioned previously (Gurnell 2002). As not all banks were digitized, watersheds with the most complete digitized banks from headwaters to mouth were chosen first. If a watershed had incomplete or undigitized banks, banks were digitized by me or undergraduate technicians using the 1 m hillshade, 1 m slope raster, and 2007 aerial photography. Hand digitization is a very time consuming and subjective process and was avoided when possible. Once a study watershed was selected, the watershed border was exported and the top of banks and centerlines were clipped to the specific watershed.

For each stream, LiDAR tiles were downloaded as LAS files from the Iowa LiDAR Mapping Project (source: http://www.geotree.uni.edu/lidar/). LAS files were processed into LAS Datasets in ArcMap. Using the “LAS Dataset to Raster” tool, I created a digital surface model (DSM) raster and a digital elevation model (DEM) raster and calculated the difference between the elevation rasters in order to determine the height of the vegetation (Figure 9). All output heights were in meters.

We used the USGS National Map Viewer to download all elevation products for hydrological analyses (source: https://viewer.nationalmap.gov/basic/). For each watershed, ⅓ arc second DEMs were downloaded. After the DEMs were downloaded, mosaicked (if needed), and projected, ESRI’s Hydrology toolset was used to calculate the flow accumulation of the watershed.

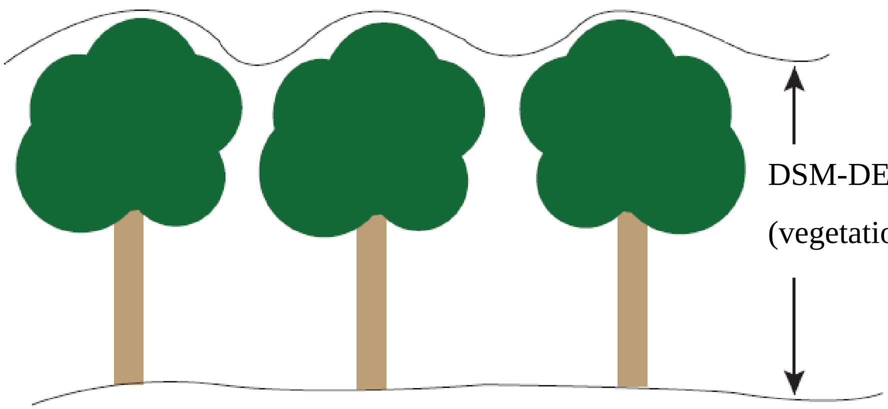

Figure 9: Geometric representation of using a DEM and DSM to estimate vegetation height created by Forrest Williams. A DEM is created the last return from a LiDAR pulse, while a DSM is created using the first return, which renders an estimation of ground elevation and vegetation elevation respectively. By subtracting the DEM from the DSM we get the difference in height between the ground and the canopy.

In order to calculate the width of the streams, Mateus Ferreira built an Arc10-compatible toolbox called "Transect Tool" that created perpendicular transects across a streamline (source: http://gis4geomorphology.com/stream-transects-partial/). Using this tool, each centerline was inputted and transects were placed every 50 m along the stream. The 50 meter transect interval was selected as appropriate size for smaller watersheds as well as larger ones. The length of the transects depended on the stream width. The transects needed to be long enough to intersect with both banks. In order to make sure the input length was long enough, the width at several locations was inspected using "Measure" before running the tool. After the tool was run, the transects were intersected with the left and right banks and the stream centerline to create 3 points at each transect (Figure 10). Stream points were always checked to ensure both banks and centerline had the same number of points and the transects intersected correctly. If errors were present, they were corrected using the "Editor Toolbar." Once this process was completed, three points were created every 50 m along the stream from the start of the bank lines to the end (Figure 10). Using the bank points, the “Generate Near Table” was run to calculate the width in meters between the left and right bank points. Using the 3D Analyst “Add Surface Information” tool, the bank points were input to obtain the previously calculated vegetation height raster information. The tool used a bilinear interpolation method which determined cell values from the four nearest cells. The selected output was the Z Max or the highest surface elevation among the interpolated values. The Z Max was used (instead of Z Mean) due to the results of Wasser *et al.* 2014, who found that for individual surveys over homogeneous vegetation types, the max height generally provided a better canopy height indicator than the average height (Wasser *et al.* 2014).

In conjunction with the LiDAR derived height values, the 2009 High Resolution Land Cover Dataset (HRLC) for Iowa was used to export land use at the bank points (source: https://geodata.iowa.gov/dataset/high-resolution-land-cover-iowa-2009). This data was preferred

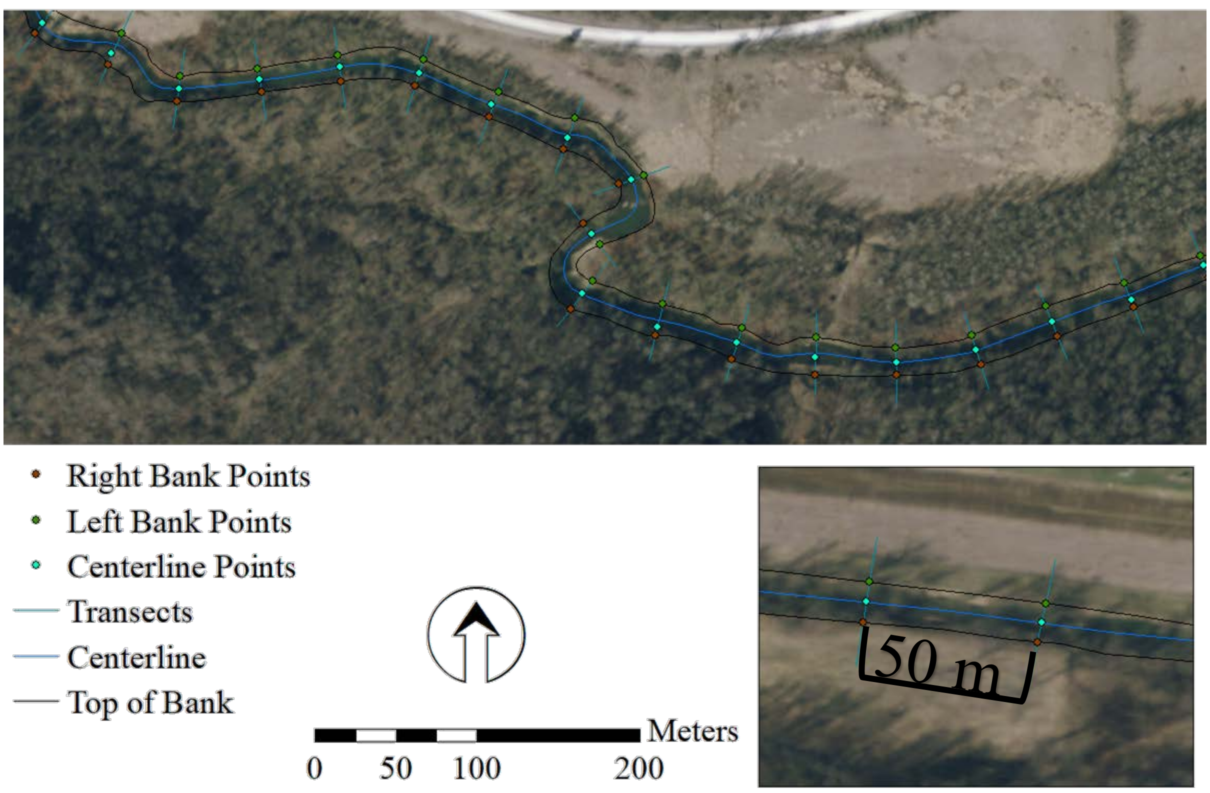

Figure 10: Example of completed transects on stream. Inset shows individual transects. Each point was standalone and a separate shapefile from each other.

over other options or years since this product was derived from three dates of aerial imagery and from elevation information derived from LiDAR elevation data. The raster values (3-6 corresponding to forest or 7-11 corresponding to grass or agriculture) were extracted to each bank point.

In order to get the upstream contributing area for each transect, the raster values from the flow accumulation along with the stream centerline points were inputted into the “Extract Values to Points” tool. This allowed for each point to be associated with a raster value. The raster value could be then be converted to upstream contributing area using the following equation:

$$\frac{(Cell\ size^2) \times (Rastervalue)}{(1000 \times 1000)} = Upstream\ contributing\ area, km^2$$

Once all three of these functions were completed, all data was exported to Excel to be organized and further analyzed. For each watershed at each transect, left and right bank points with land use characteristics (LiDAR derived height and HRLC land cover raster values), width, and flow accumulation were available. The number of transects varied from 48 to over 4000 depending on the length of stream. This entire process was repeated several times on a total of 20 streams in Iowa.

Finally, in an attempt to re-create the results found by Trimble 1997 using my methodology, I also completed the data collection process on the lower end of Coon Creek in Wisconsin (Figure 11). This process followed the same methodology presented here and was kept separate from all Iowa data calculations and statistics. All LiDAR and shapefiles were provided by Vernon County Land Information Office (source: http://www.vernoncounty.org/LIR.htm). The 2001 NLCD was used for Coon Creek as it was only 4 years after Trimble’s study and no HRLC was available for Wisconsin.

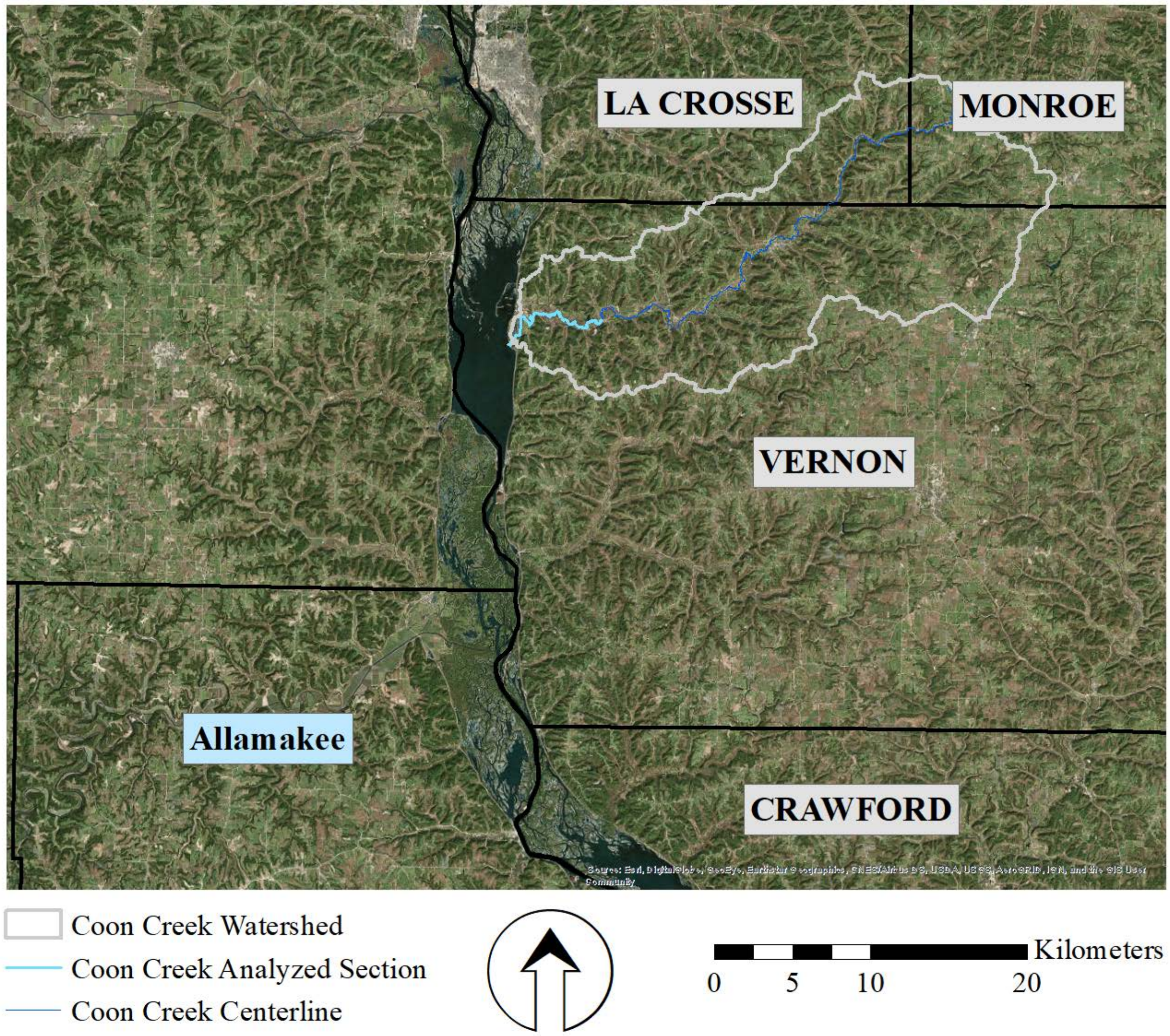

Figure 11: Coon Creek watershed (white outline), which spans three Wisconsin counties. Blue text box indicates Iowa county. Mississippi River creates the boarder of IA (left) and WI (left).

Appendix A contains flow chart of GIS methodologies.

2.3 Geospatial Data Manipulation

As discussed previously, drainage area is positively related to channel width:

$$w = \alpha A^{\beta}$$

Due to the lack of availability of stream gauges within the 20 selected watersheds, drainage area was used to create DHG curves for each stream and compute their power-law regression functions. A state wide regional DHG curve was also created.

Since channel width is expected to vary systematically with drainage area, in order to detect vegetation effects on channel width, drainage-area effects had to be removed from the data. We chose to do that by computing deviations from the empirical best-fit regional DHG equation for measured widths and investigating the relationships between those deviations and vegetation. We also computed ratios of the actual to predicted width values calculated also using the best-fit regional DHG equation.

For example, if the drainage area of a point was 100 km^2 and the width was 16.9 m:

$$\hat{y} = 2.7361(100^{0.4067})$$

$$\hat{y} = 17.80$$

$$Residual = y - \hat{y} \qquad Ratio = \frac{y}{\hat{y}}$$

$$Residual = 16.9\,m - 17.80\,m \qquad Ratio = \frac{16.9\,m}{17.80\,m}$$

$$Residual = -0.9\,m \qquad Ratio = 0.949$$

A higher residual value and a ratio value ≥ 1 indicate locations where the stream width is greater than the best-fit width from the empirical regression. These values would later be the basis of statistical testing. It should be noted that residuals were also calculated on a watershed basis using individual watershed DHG curves, but were ultimately not used.

Following similar studies, the continuous variable of canopy height was split into two distinct land cover classes: forest and grass (Trimble 1997). Since my data were collected geospatially on such a large scale, LiDAR canopy height values were classified. If the LiDAR value was higher than 3.5 m, the point was characterized as “forest”. If the value was below 3.5

m, it was characterized as “grass”. These classifications were referred to as “grades.” The value of 3.5 m was chosen due to potentially exclude crops as well as follow similar methodology to the Iowa DNR (personal communication with C. Wolter 2017).

As the HRLC raster values were already categorical, re-classification was not needed; however similar categories were grouped for the purpose of the research. For the HRLC, all values 3-6 were listed as “forest” and all values 7-11 were listed as “grass”. The corresponding classification of “forest” or “grass” were referred to as “land use.” The NLCD also returned other values (such as 1- urban) which were labeled “false”. These rows where “false” values were identified and ultimately removed.

Four other variables were created using the grade and land cover data. The first variable (“grade winner”) calculated the maximum LiDAR height between left and right banks then classified the value as either “grass” or “forest”. The second variable (“land use winner”) first converted each bank’s HRLC value converted to binary (Forest=1, Grass=0) and then took a maximum calculation between the two bank cells. If the value was a 1, this indicated one of the banks was forested, and then was termed “forest”. If the value was 0, it was categorized as “grass”. Both “grade winner” and “land use winner” only returned the forest classification when *either* one of the banks was forested. In order to explore when *both* banks were forested, two final variables were created. One variable took the sum of the HRLC binary variables described previously and then used an IF formula to categorize a value of 2 (both banks forested) as “forest” and a value of 1 or 0 as “grass”. This variable was termed “hrlc winner”. The other, “lidar winner”, was similarly created, but used a binary output of the LiDAR data (Forest=1, Grass=0). Table 4 gives an overview of all the GIS variables and their labels.

Table 4: All variables and labels derived from GIS methodology.

Variable label	Description of variable
res	Residuals calculated from actual stream width and predicted stream width from state DHG
ratio	Ratio calculated from actual stream width and predicted stream width from state DHG
grade winner	Maximum LiDAR value between LB and RB
land use winner	Between LB and RB, forested HRLC value (if present)
lidar winner	Only if both LiDAR values classified as “forest”
hlrc winner	Only if both HRLC values classified as “forest”

2.4 Statistical Methods for GIS Data

In order to evaluate if the GIS derived width residuals were a significant method of predicting the probability of land use on either bank, logistic regressions were run in the statistical software SAS. A logistic regression is a predictive analysis used when the dependent variable is dichotomous or binary. A logistic model can be used to assess the odds ratio of predictors as well as determine the probability of response variable(s) occurring due to specific predictor values (Hilbe 2016). Logistic models are parametric and follow a binomial distribution. The general equation of a logistic regression is as follows:

$$ln\left(\frac{\mu_1}{1-\mu_i}\right) = \hat{\beta}_o + \hat{\beta}_1 x$$

For a logistic model, μ is defined as the probability that $y = 1$, where y is the representing the model response term (Hilbe 2016). The term μ_1 would indicate the presence of the response variable while 1-μ would indicate an absence. The left side of the equation is the log of odds or *logit*. Each β is a term indicating the value of a coefficient (β) and its predictor or slope (x).

In order to evaluate the strength of the association between the channel width and the riparian land use, land use was treated as the response variable while the width residuals and ratio were treated as the predictor or independent variable. The goal was to find the best fitting model to describe the relationship between the presence of forest and the calculated width residuals. The equation of my logistic regression was:

$$\log\left(\frac{P(Forest)}{P(Grass)}\right) = \hat{\beta}_o + \hat{\beta}_1 x$$

Where P is the log-odds probability of the presence of forest or the absence of forest (grass). Since land use was my only predictor, we were only concerned with one β coefficient and slope, $\hat{\beta}_1 x$. We then solved for the *logit* function:

$$P = (Forest|Grass) = \frac{e^{\hat{\beta}_o + \hat{\beta}_1 width}}{1 + e^{\hat{\beta}_o + \hat{\beta}_1 width}}$$

This equation is what ultimately my SAS model was calculating. The slope ($\hat{\beta}_1$) is the value of the rate of change in the probability of the presence of forest (*y*) when width residuals/ratio (*x*) moves from 0 to 1. Since the log-odds of the slope is not very descriptive, once the values are exponentiated, the odds of the presence of forest (*y*=1 or 0) can be interpreted. Our hypotheses were:

H_o= *Width residuals and ratio are not a significant method to predicting land use*
H_a = *Width residuals and ratio are a significant method to predicting land use*

The SAS GLIMMIX procedure was chosen to run the logistic regression. It performs estimation and statistical inference for generalized linear mixed models like a logistic regression. Using the GLIMMIX procedure, land use, watershed, and transect were all treated as categorical variables in order to create levels within the model. A binary distribution and Kenward and Rodger's 1997 method for computing the denominator degrees of freedom were used and the solutions for the fixed-effects parameters were produced to include their estimated standard errors and t statistic. The transects within each watershed were treated and specified as the random repeated effect in the model to allow for ordering of the covariance structure. Complete independence was assumed across watersheds and each watershed was used as a subject to block the variance matrices which nested all transects within the watershed effect.

The GLIMMIX procedure then modeled the probability that the land use was forest with regressor as the width residuals or width ratio. The same model was run several separate times changing the dependent and independent variables. In order to examine the LiDAR and the HRLC, all four variables ("grade winner", "land use winner", "hlrc winner", and "lidar winner") were tested as the response variable.

For Coon Creek in Wisconsin, a similar model was used, but since only one watershed was being tested, the matrix was blocked diagonally.

2.5 Field Methods

Field collection took place from May through August of 2018. Surveyed channel segments were distributed across the entire state of Iowa and the various landform regions (Figure 12). Sites were selected due to availability of access, landform region, wadeability, and riparian land use type. Travel time to each site from Ames was also taken into consideration.

Site selection began by viewing watersheds and streams on ArcMap, Google Earth, and cross-referencing public lands in Iowa. Areas of streams within public areas were prioritized. If stream length within the area was an appropriate length (>370 m), a randomization selection process took place. If stream length was not long enough, the public access area simply was used. One privately own property was visited. Before traveling to the site, aerial imagery was used to decide best access point as well where the surveyed reach would begin.

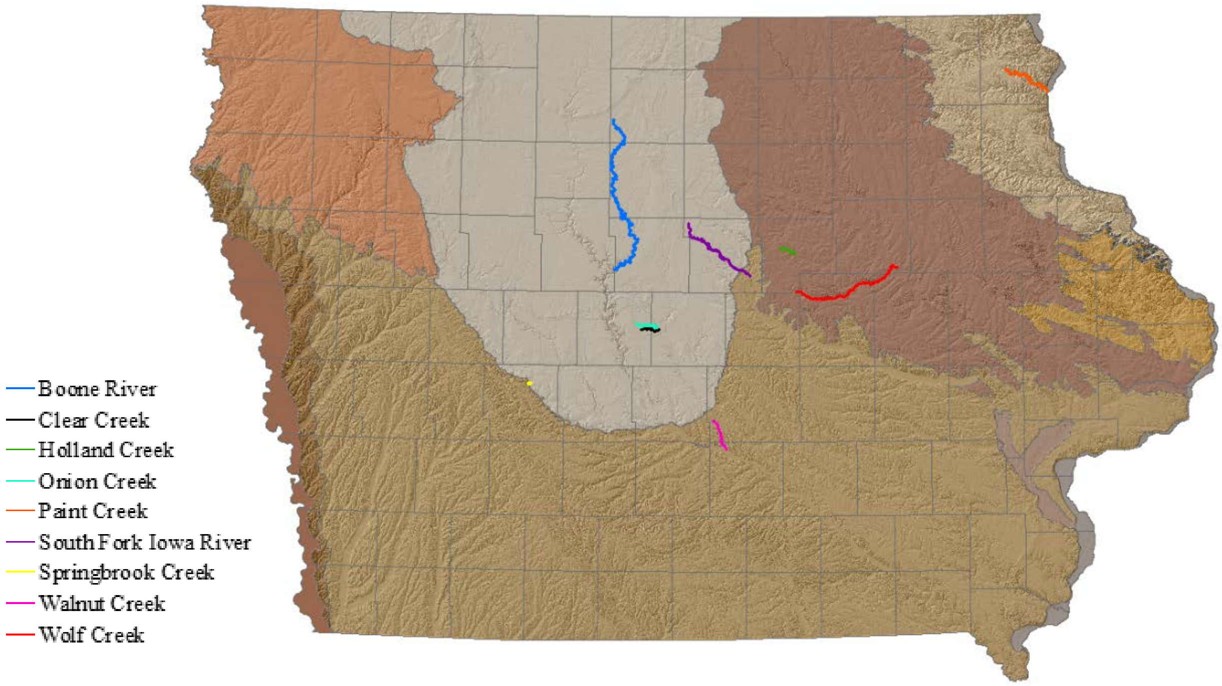

Figure 12: Map of field 10 field sites. Onion Creek in light blue contained two field sites.

On-site methods loosely followed the Iowa DNR's Biological Sampling and Physical Habitat Assessment Standard Operating Procedures for Wadeable Streams and Rivers and the United States EPA's National Rivers and Streams Assessment 2013/14 Field Operations Manual. Once at the site, an average top of bank width was taken either with a laser clinometer (if width >10m) or by stretching out a tape from top of bank to top of bank at several locations. This average width was multiplied by 30 in order to determine the reach length following Iowa DNR protocol (Iowa DNR 2015). A tape was then stretched out in the stream bottom for the calculated reach length; following the thalweg of the stream and being pinned when necessary. Stations of 50 m were indicated with survey flags as well as "facets" including riffles, pools, log jams, or other areas of interest within the stream.

The long profile of the stream was surveyed using an auto level and stadia rod. Beginning at the origin, every 5 m the bed surface and water surface elevation were recorded (Rosgen 2007). The bed surface was taken at the deepest section of the stream within the thalweg. If velocity of the stream was too fast or location was too deep for the technician, measurement was moved to the next best location. Additional survey points were taken at stream facets within the reach. The process was completed once the end point of the stream section was reached.

Approximately 10 cross sections of the stream were recorded for each reach. Cross sections were placed within riffles, directly downstream of dam jams (if present), across channel cut offs, and other areas of geomorphic interest (Rosgen 2007). Once location was chosen, station location was indicated and bankfull indictors on each bank were marked. Presence of perennial vegetation, lower tree roots, and change in sediment texture (i.e. presence of fresh alluvial sand) were used as bankfull indicators (USEPA 2013). If bankfull was not obvious at location, upstream and downstream banks were considered in order to estimate. General notes on bed material at cross section located were also noted.

In order to measure the top of bank and bankfull widths, a cloth tape was stretched across the stream perpendicular to the flow. The tape was then pulled taut and leveled using a bubble level and adjusted accordingly using a nearby tree or gardening t-post for anchoring. Starting on the left bank, a survey point was taken with a stadia rod every 1.0 m out of stream and every 0.5 m within the stream (Iowa DNR 2001, Rosgen 2007). The top of the bank (where slope changed or dropped off), bankfull (previously flagged), and the edge of water were all also surveyed. This repeated process allowed for the calculation of the top of bank width, bankfull width, graphical interpretation of the stream cross-section, average water surface elevation, as well as average bankfull slope across the reach. When entering data, if large discrepancies between the water surfaces were present (greater than 0.1 m) a correction formula was used in order to appropriate the data points.

It must be noted when completing the field site on the Boone River, we were unable to perform cross-sections using the method detailed above as the river was over 60 m wide in places. One transect was attempted (with four people) and the tape snapped. Instead, two people stood on either side of the bank, one with the laser clinometer and the other indicating the top of bank and bank full using their body as a target for the laser. The person shooting the laser changed positions for both bank measurements in order to get the shot as level as possible. This process was repeated several times to get several measurements.

To order to understand the potential impact on morphology, LW variables were recorded throughout the reach of the stream beginning at the origin (Gurnell *et al.* 2002, Wohl 2017). While walking through the stream, all LW within zones 1, 2, 3, and 4 were tallied and recorded (Figure 13, Schuett-Hames *et al.* 1999). Following similar studies, several basic variables including: the side of the stream channel a wood piece was present on, piece length (m), diameter (cm), presence of roots, and position and orientation to stream channel were recorded for individual LW pieces (Schuett-Hames *et al.* 1999, Magilligan *et al.* 2008). Decay class (I-V) following Schuett-Hames *et al.* 1999 was also recorded. Other variables recorded were anchoring type (buried, within bank etc.), the presence (or absence) of pooling, sedimentation, and scouring upstream and downstream of wood were all recorded for each individual piece (Schuett-Hames *et al.* 1999, Magilligan *et al*. 2008). Other specifics were recorded such as station location and the species of the tree, if bark was present, or beaver signs.

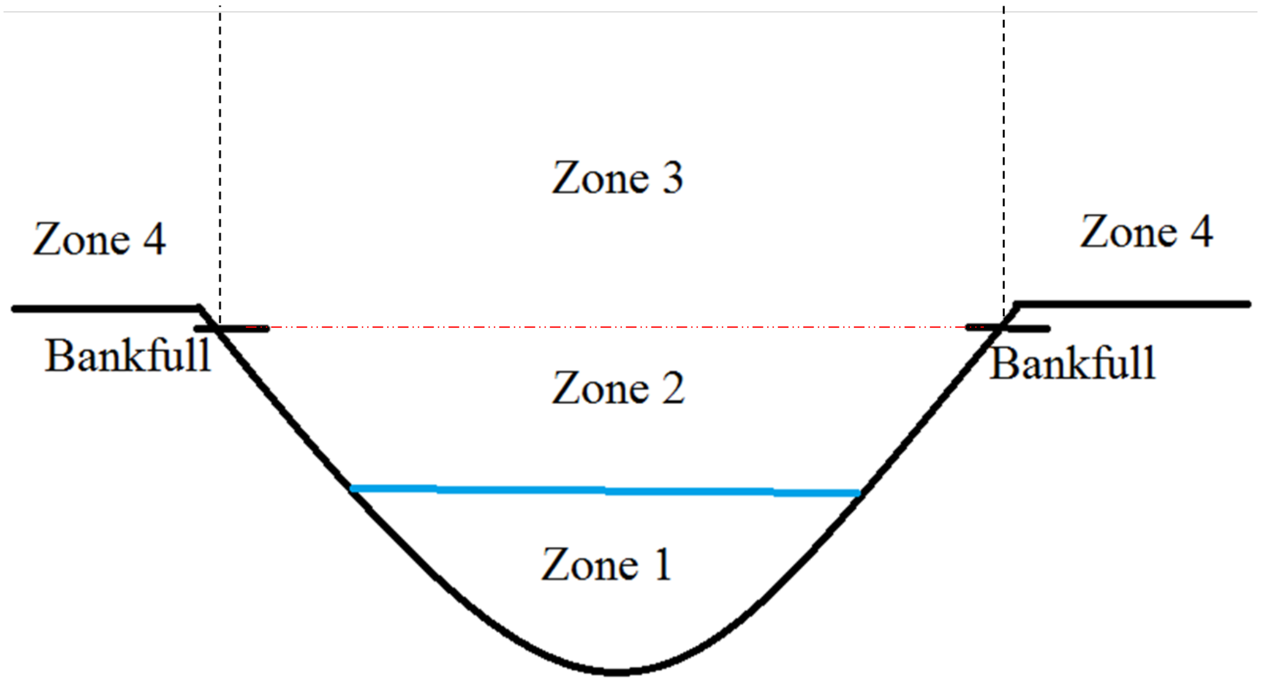

Figure 13: Diagram of LW zones adapted from Schuett-Hames et al. 1999. Zone 1 is within the wetted channel during the survey (flow dependent). Zone 2 is within the area above the wetted channel, but below the bankfull calls indicated by the red dotted line. Zone 3 is anywhere above Zone 2, including channel spanning pieces. Zone 4 is the floodplain and riparian areas.

If a jam was encountered, the jam was analyzed to determine the key piece or the stable piece of LW forming the anchor and keeping the jam in place. Position of the pieces, age, decay class, and visual indicators were all used to determine the key piece(s) (Gurnell *et al.* 2002). It was occasionally observed that some dam jams had multiple key pieces. Characteristics of the key piece were important to record as we might infer that key pieces are near the optimal length for getting stuck in the channel – too short to perch above the channel, but too long to get floated or rotated away. The qualifying pieces within the jam were tallied according to their zone as well as their length and diameter. The key piece(s) of the dam jam were given special attention. A tape measure was stretched along the key piece and the entire length was recorded as well as the length within the four zones. The diameter of the key piece was taken using a Biltmore stick; if roots were present, diameter was taken at approximate breast height. If no roots were present, several diameters were measured along the piece and averaged. Decay class, presence of roots, potential location of origin, position and orientation to stream channel, anchoring type, and the presence (or absence) of pooling, sedimentation, and scouring upstream, downstream, and within jam were all recorded for each key piece. If it was possible, the height of the banks was measured at the center of the jam using a stadia rod. Top of bank widths were also measured with a laser clinometer above, within, and below the dam jam noted by station number. A photo with a GPS-enabled digital camera was also taken of the jam from downstream and upstream angles.

Riparian forestry plots were measured on each bank to characterize the forests from which LW pieces were likely recruited (Magilligan *et al.* 2008, Iowa DNR 2015). Plots were chosen to be in areas which represented majority of the riparian land use of the reach. The first plot began 7.5 m away from the bank of the stream. From this center point, a 50 m transect was measured; marking two addition center points at 25 m and 50 m. These center points were checked and adjusted to also be 7.5 m from the stream bank by measuring. From each center point, 7.5 m was measured and flagged to create a circular plot extending 15 m in total from stream bank. Once three plots were created and measured out, the canopy density was taken at the bank as well as the center point using a convex densitometer (averaging over all four directions). Next all trees $\geq$ 10 cm in diameter within the plot were measured at breast height using a Biltmore stick. The heights of the trees were measured using a laser clinometer. Tree species and condition were recorded. If standing trees were dead, identity of species was attempted as well as reason for mortality. A running tally of coarse woody debris on the forest floor ($\geq$ 1 m in length and $\geq$ 10 cm in diameter) was also kept for each plot. This process was repeated for each plot.

Also within each plot, Field Form H from the Iowa DNR's Biological Sampling and Physical Habitat Assessment Standard Operating Procedures for Wadeable Streams and Rivers was used in order to "grade" the riparian land use within the plots (Source: http://publications.iowa.gov/20274/1/Bioassessment_SOP_final.pdf, pg. 64). Within the three plots on each bank a grade (0=absent, 1= sparse (<10%), 2= moderate (10-40%), 3= heavy (40-75%), and 4 = very heavy (>75%)) was assigned for several categories like canopy cover, understory, groundcover, and human influences. This form allowed for quick comparison between watersheds and banks.

2.6 Field Data Evaluation

Data was input into Excel sheets after each field site was finished. Once all 10 sites were finished, data organization and analysis began. In order to analyze any significant trends in the large abundance of field data, many new variables were created such as averages and totals. Riparian vegetation data including bank and plot density, DBH, height, CWD, and calculated basal area were all averaged across banks within reaches. Specific jam variables such as presence of pools, sedimentation, and scouring, orientation, zone location, decay class, number of key pieces, length and DBH of key piece, and number of pieces within a jam were totaled and averaged for reaches and volumes were calculated when applicable.

Summary tables for each reach were created including: the drainage area of the reach (km^2), the total length of the reach (m), the area (m^2) of each reach (calculated using the total length and the average bankfull width), and following similar studies, (Magilligan *et al.* 2008, Livers *et al.* 2018), variables were created for total LW pieces, total jams, and total CWD per 100 m for each reach and reach area. Volume of LW pieces was also calculated assuming that LW pieces were cylindrical:

$$V = \pi r^2 L$$

Where r is the radius of wood pieces (m) and L is the total length (m). These averaged variables allowed for general comparison across reaches no matter their drainage area or reach length. To ensure comparability to other LW studies, we also calculated LWD volume per unit stream area (m^3m^{-2}) and LWD abundance per unit stream length ($\#m^{-1}$).

To analyze reach-scale impacts, stations within reaches were utilized. Two main objectives were analyzed at the reach-scale level: the impact on channel width from LW jams and the number of pieces of LW and the number of jams.

For the impact due to the presence of jams, each reach's cross-section data was compiled together to create a four column table. Watershed name, station number, width (m), and presence of jam (Y/N) were recorded for all 10 sites. To normalize the width for this analysis, two methods were used. One utilized the power law regression equation from the hydraulic geometry relationship between all 10 field sites. For this method, the drainage area of the reach was used to calculate the reaches' calculated residual width. The calculated width was then used to normalize the width measurements within that specific reach. The other method consisted of dividing each individual reach value by the average from that specific reach.

In order to facilitate statistical investigation of reach-scale variables, each station needed to be a standalone data entry. To do this and to normalize the number of pieces of LW and the number of jams per reach, a technique was created wherein for each station, the number of pieces of LW and jams were tallied within half the distance between the previous and next station (Figure 14). Since some values calculated using this method were very small, values were scaled up to 100 m by using the equation:

$$\frac{LW}{100\,m} = \frac{100}{x} \times\ p$$

Where x is the length of the station's segment and p is the pieces of wood or number of jams.

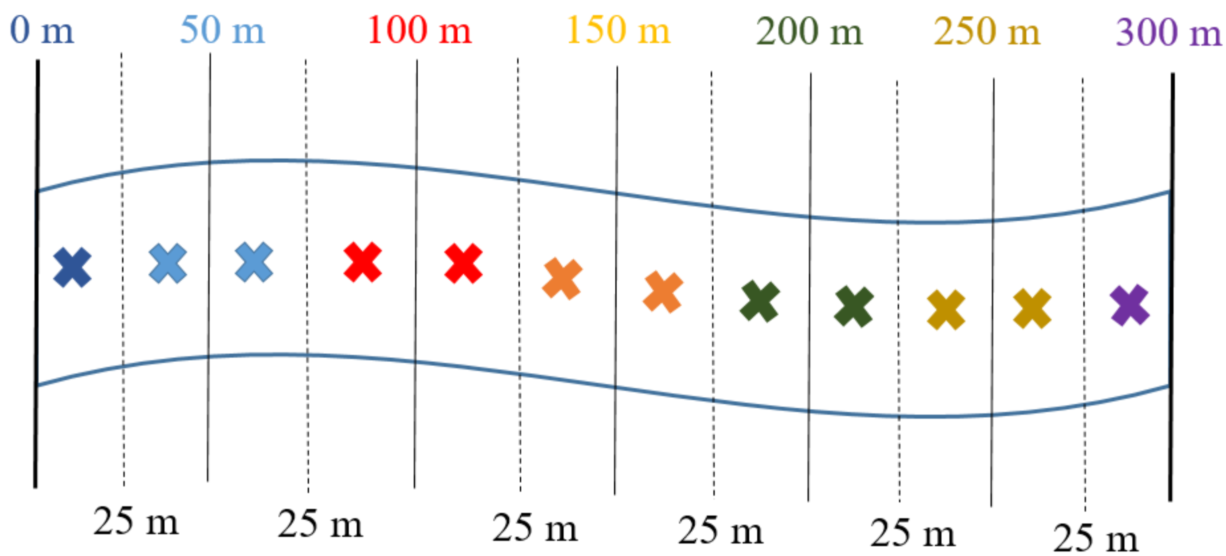

Figure 14: Simplified diagram of LW-station tally method. Color of x's correlate with the station color. Jams and LW would be tallied for corresponding sections. Origin and last station only had one section.

2.7 Statistical Methods for Field Data

A. Width at jams

To analyze the effect of jams on top of bank and bankfull width, generalized linear mixed models (GLM) were run in SAS. The general equation of a Gaussian GLM is:

$$y = \beta_o + \beta_1 I$$

Where y is the response variable, β are parameters, and I is the exploratory or independent variable. For my data, width was treated as the response variable and jam presence (Y/N) as the predictor:

$$Width = \beta_o + \beta_1 I \ (Jam = Y/N)$$

Both methods of width standardization mentioned previously were tested separately in the model. The watershed and station number were included as random effects as to represent the influence the location may have on the observations. Restricted Maximum Likelihood (REML) was used as the estimation technique. Kenward and Rodger's 1997 method for computing the denominator degrees of freedom was used in the model as well as the solutions for the fixed-effects and an LSMEANS statement in order to produce the Least Square Means and the Differences of the jam Least Square Means in the results.

Within the model, if jam = Y,

$$(Jam = Y) = \frac{0\ if\ there\ is\ a\ jam}{1\ if\ there\ is\ not\ a\ jam}$$

$$Then, Width = \beta_o + \beta_1(0)$$

Both values of β_o and β_1 along with their *p*-values are recorded in the SAS output. These *p*-values indicated if streams were significantly wider in locations with jams. The LS-means are the adjusted predicted mean width values when there is a jam vs. no jam while also taking model parameters into consideration.

B. Width, large wood, and riparian area

In order to investigate all other variables that were not station-specific, simple correlations were tested in R. Normality was tested using a Shapiro–Wilk test for each variable. If variables failed and were to be used as a response variable, a Spearman's non-parametric correlation test was used in place of a Pearson's correlation test. Normality was also checked using Q-Q-plots as well as well as plots to check for constant variance of residuals.

All model code can be found in Appendix A.

CHAPTER 3: RESULTS
3.1 Results of Geospatial Analysis

Table 5 contains the coefficient values for the individual empirical best-fit DHG equations for measured widths on the 21 Iowa streams and Coon Creek in Wisconsin. The streams with an asterisk were not included in the creation of the regional DHG (Figure 15) due to questionable high α and/or negative β values.

Table 5: Downstream hydraulic geometry coefficients and R^2 values.

DHG	**α**	**β**	**R^2**
Big	1.8609	0.5194	0.7094
Boone	4.1873	0.3576	0.8056
Buffalo	3.9721	0.3774	0.3306
*Clear**	23.1370	-0.3840	0.1518
Holland	2.3350	0.2667	0.2538
*Jack**	127.4100	-0.3250	0.1829
Maple	1.5847	0.4581	0.8258
*Nishnabotna**	38.2110	0.0320	0.0114
Nodaway	1.8994	0.5046	0.5803
*Onion**	8.3585	0.0889	0.0233
Otter	1.5496	0.5581	0.8156
Paint	6.6062	0.1973	0.3049
Plum	2.7170	0.4388	0.0459
*Prairie**	24.8460	0.0401	0.0211
Rock	3.9607	0.3159	0.3882
Southfork	3.1565	0.3631	0.4376
*Springbrook**	9.8817	-0.2770	0.0738
*Turkey**	26.2590	0.1398	0.3033
Walnut	2.1572	0.3767	0.4867
Wolf	3.4370	0.3443	0.6127
Yellow	3.5440	0.3360	0.7300
State regional (14 WS)	2.7361	0.4067	0.6851
Coon (Wisconsin)	5.6739	0.1023	0.0022

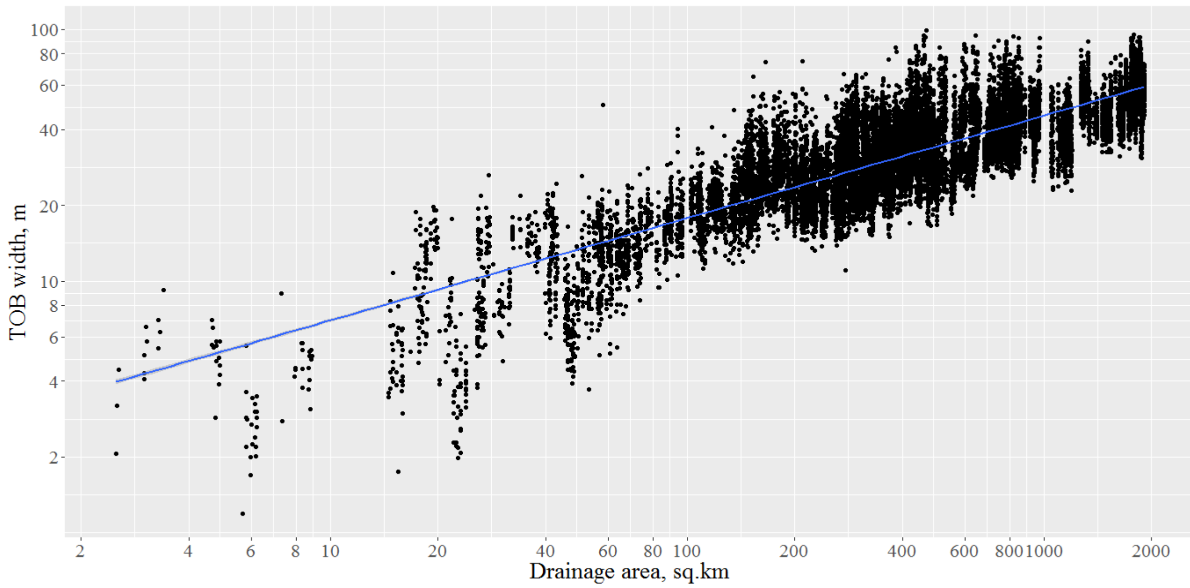

Figure 15: Regional DHG curve containing 14 watersheds in Iowa representing various landform regions.

No obvious differences between watersheds appeared in the calculated width residuals (Figure 16) or the calculated ratios (Figure 17).

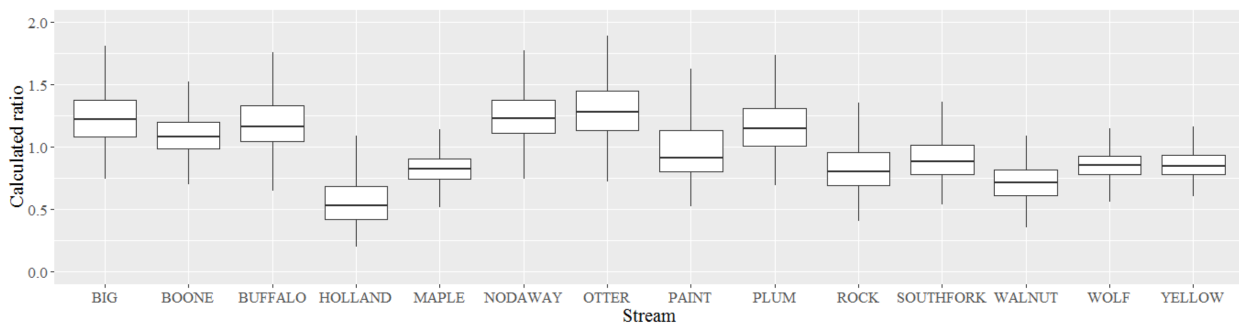

Figure 16: Boxplots of calculated width residuals for all 14 streams

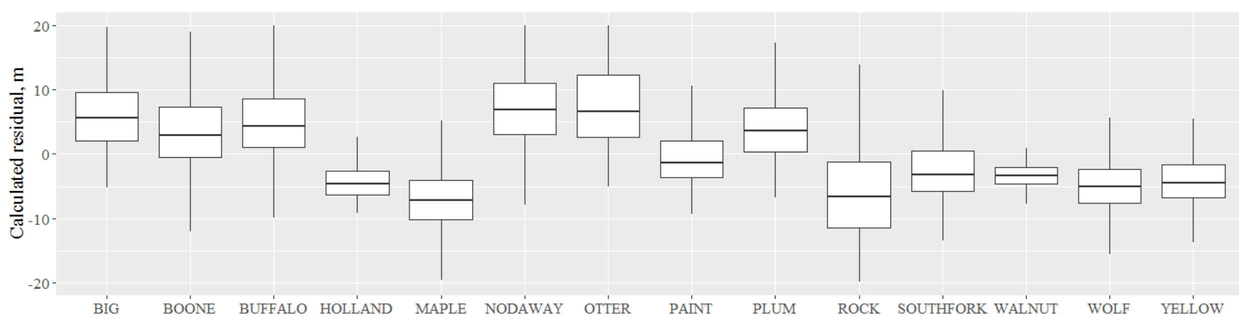

Figure 17: Boxplots of calculated actual-predicted width ratio for all 14 streams

A logistic model is presumed to fit the data well when three qualifications are met: the predictors are uncorrelated with one another, the observations of the model are also uncorrelated, and the predictors are significantly related to the response variable (Hilbe 2016). The structure of the logistic model was created so that the first two qualifications would be met automatically. The third was calculated by each model as a Type III Test of Fixed Effects. For all models ran with Iowa data, the predictors were shown to be significantly related to the response variable or in the case of my research, width residuals and width ratio were shown to be significant criteria for evaluating the probability that the surrounding banks were forested (Table 6). This significance allowed me reject my null hypothesis and continue on to interpret my log-odds ratios.

For each model ran in SAS, an intercept, slope, and their corresponding t-values and *p*-values were produced. All *p*-values, for intercepts and slopes, were shown to be significant (α=0.05). The slopes of all the models were also positive. Once converted, an odds-ratio can be transformed into a percent to understand the probability of the response variable occurring (y=1). This allows for a more understandable comparison. All results in Table 6 can be interpreted in the same manor: the relative odds of the land use being forest increases by the percent increase when a one unit increase of the predictor variable occurs. When grade winner is inputted as the response variable and width residuals as the predictor, a one meter increase in residual width, increases the relative odds of the land use being forest by 4.34%. Graphical representations of the logistic models were created with the y axis representing the probability of the forest and the x axis as the width residuals or ratio (Figure 18, 19).

Table 6: Results table of logistic regression for GIS derived data. Response variable indicates the method the land cover was derived and predictor designates whether the width residuals or ratio were used. 14 watersheds were included and 16729 transects were analyzed for each model.

Response variable	Predictor variable	Odds ratio	*p*-value of odds ratio/fixed effects slope	Percent increase
grade winner	res	1.0434	<0.0001	4.34%
grade winner	ratio	3.6851	<0.0001	268.51%
land use winner	res	1.0352	<0.0001	3.52%
land use winner	ratio	2.6480	<0.0001	164.80%
lidar winner	res	1.0320	<0.0001	3.19%
lidar winner	ratio	2.4925	<0.0001	149.25%
hrlc winner	res	1.0273	<0.0001	2.73%
hrlc winner	ratio	2.1928	<0.0001	119.28%

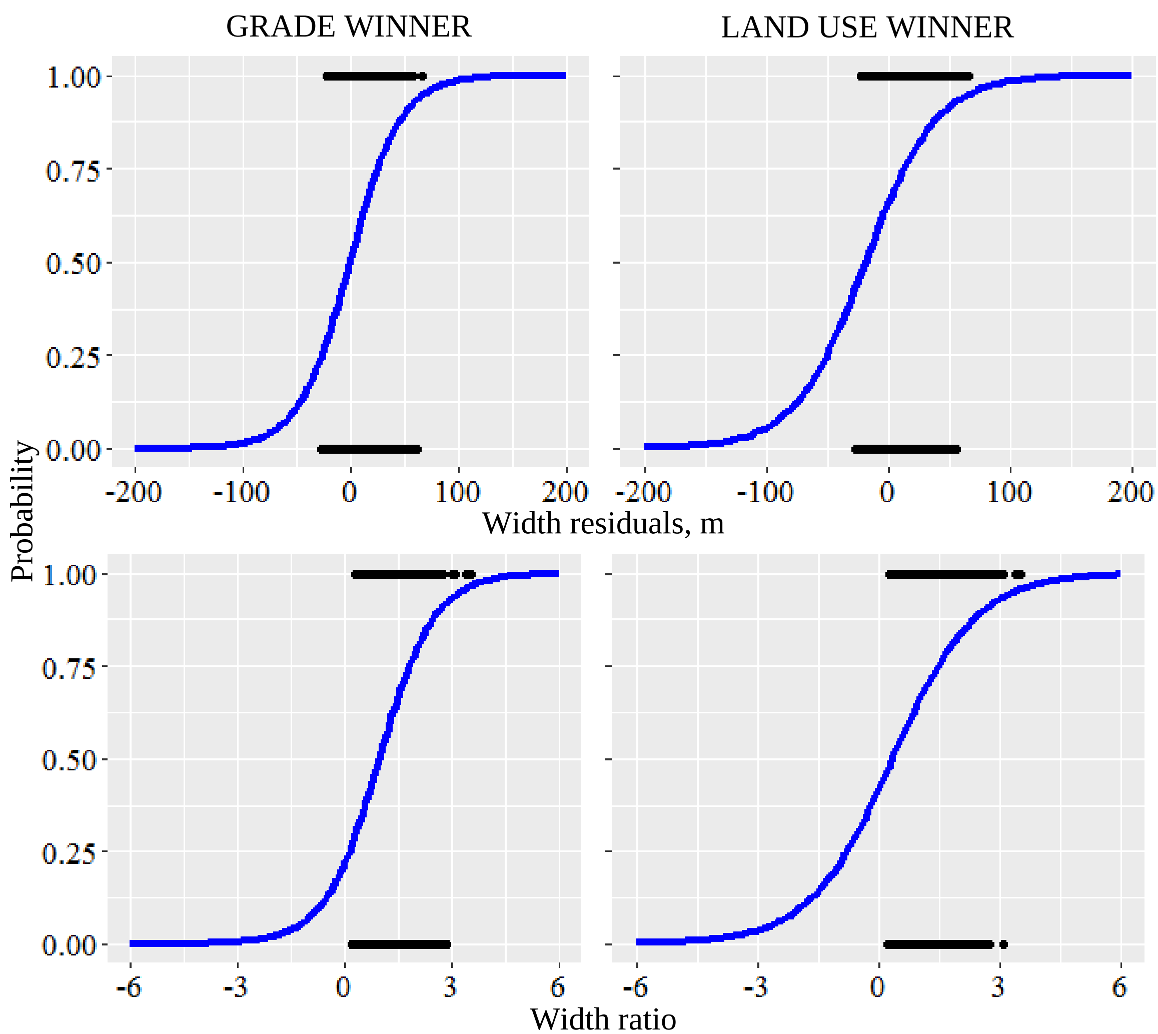

Figure 18: Graphical representations of logisitc regressions. Left column used grade winner as the predictor and right column used land use winner. X-axis is the width residuals (top) and width ratio (bottom) and Y-axis is the probability of the riparian vegetation being forest. The sigmodial curve can be used to make predictions. SE too small to graph.

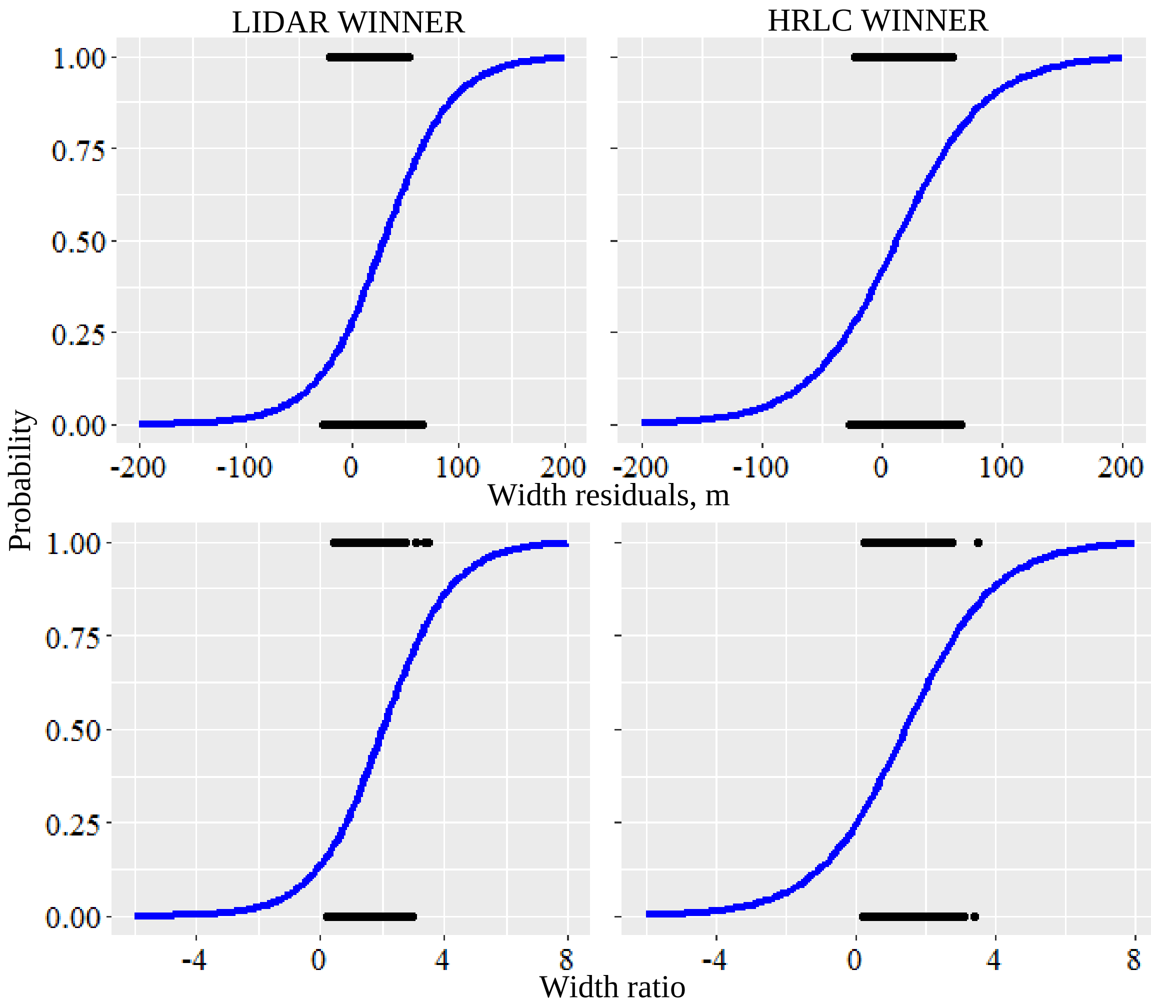

Figure 19: Graphical representations of logisitc regressions. Left column used lidar winner as the predictor and right column used hrlc winner. X-axis is the width residuals (top) and width ratio (bottom) and Y-axis is the probability of the riparian vegetation being forest. The sigmodial curve can be used to make predictions of probabilty. SE too small to graph.

A. Coon Creek, Wisconsin

Table 7 contains all Coon Creek results. All *p*-values, for intercepts and slopes, were not significant (α=0.05). The slopes of the models varied. Models which used grade winner (and included value 90) as their response were positive. All other models had negative slopes. Figure 20 displays boxplots for calculated residual values when using grade winner (left) and land use winner (right) as the response variables.

Table 7: Coon Creek results. Models analyzed 1311 transects. "No 90" refers to the exclusion of the raster value 90 (woody wetlands). Red indicates a negative odds ratio and probability.

Response	Predictor	Odds ratio	Probability	*p*-value
Grade winner	res	1.0151	1.5113 %	0.5116
Grade winner	ratio	1.1640	16.4044 %	0.5156
Land use winner	res	0.9871	1.2916 %	0.4014
Land use winner	ratio	0.8761	12.3922 %	0.4040
Grade winner (No 90)	res	0.9931	0.6926 %	0.8162
Grade winner (No 90)	ratio	0.9294	7.0610 %	0.8105
Land use winner (No 90)	res	0.9622	3.3780 %	0.4274
Land use winner (No 90)	ratio	0.6778	32.2198 %	0.4327

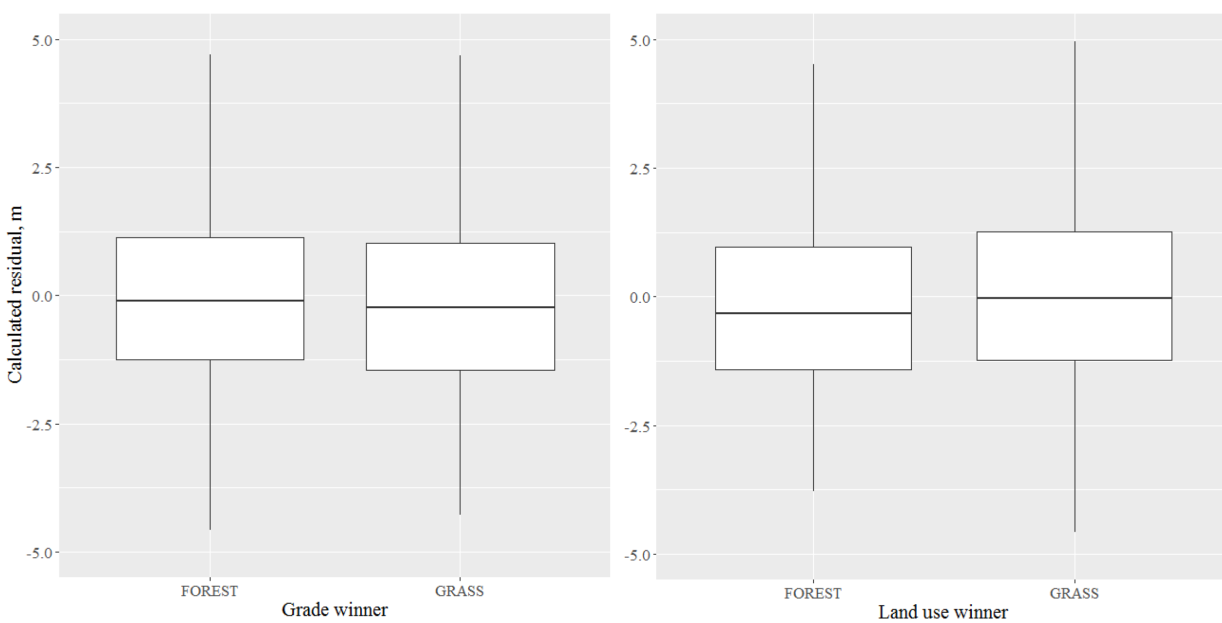

Figure 20: Coon Creek Grade winner (left) and land use winner (right) plotted against calculated width residuals. Notice land use winner's grass contained a higher median residual value compared to grade winner.

3.2 Results of Field Analysis

A. Stream cross-sections

A total of 93 cross-sections were measured within our 10 field streams. Table 8 details channel measurements from each site. Using the drainage area from the end of each reach (column 2), and the top of bank width, a DHG curve was created for all field sites. The field points are plotted with the state regional DGH in Figure 21.

Table 8: Physical stream variables collected at field sites. Normalized width was calculated using the field DHG curve power law equation.

Stream	Drainage Area, km²	Reach Length, m	Average width, m		Standard Deviation		Normalized width, m	STD BF Depth
			TOB	BF	TOB	BF		
Onion	11.23	300	8.18	6.55	1.56	1.33	7.45	0.15
Springbrook	17.18	240	9.67	7.05	1.21	1.4	8.70	0.18
Clear	17.80	200	9.60	7.75	2.08	2.14	8.81	0.03
Onion2	28.05	300	11.95	9.55	1.28	1.37	10.40	0.15
Walnut	41.33	350	11.23	6.07	1.7	1.38	11.99	0.18
Holland	48.03	300	9.26	6.05	2.16	1.72	12.66	0.10
Wolf	156.47	300	16.37	13.25	1.7	1.75	19.50	0.13
Paint	191.19	370	23.63	19.45	5.95	8.67	20.98	0.22
Southfork	302.78	370	19.97	16.87	4	1.97	24.82	0.19
Boone	1902.37	370	60.97	55.13	3.22	4	48.57	N/A

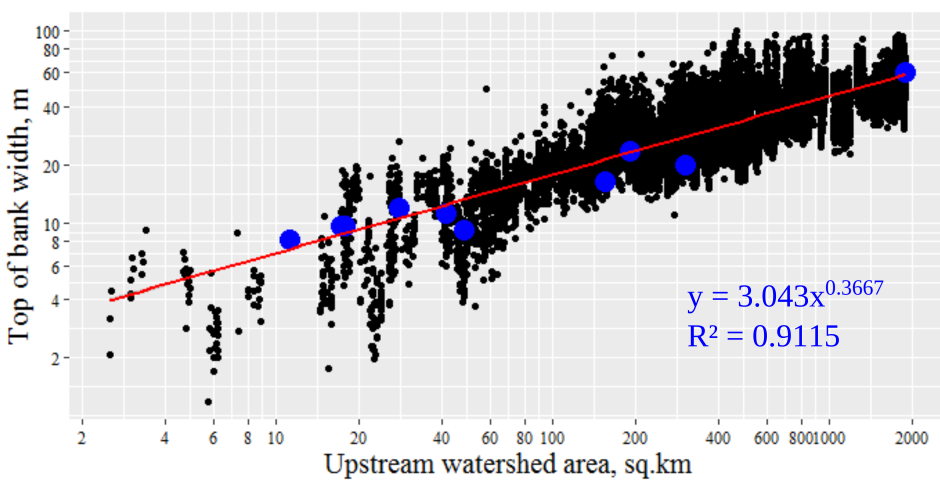

Figure 21: Regional DHG and Field DHG. Field sites in blue, GIS points in black.

B. Riparian forestry

A total of 357 trees were measured over the course of the field collection. The percent of all tree species observed are summarized in Figure 22. Boxelder (*Acer negundo*) was the most common species of tree, followed by elms (including rock, slippery, and black), and honey locust. The average tree DBH was 27.46 cm and the average height was 11.757 m (Table 10). Specific forestry measurements for each individual reach are summarized in Appendix B.

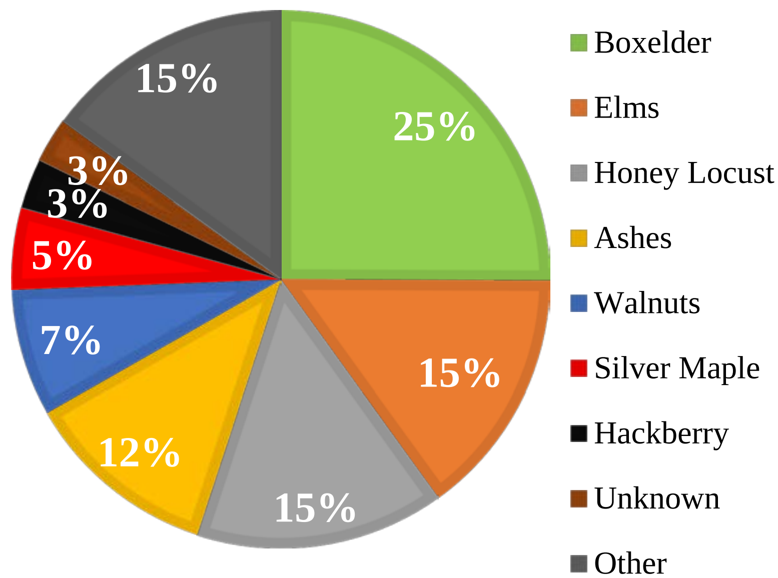

Figure 22: Pie chart of observed riparian trees. "Other" includes hawthorn, ironwood, mulberry, buckeye, black cherry, basswood, cottonwood, and willows.

. *Table 9: Forestry measurement overview. Three plots on each bank averaged. Holland Creek not included due to lack of trees*

Stream reach	**CWD/ 100m**	**CWD/ area**	**Avg. bankdens (%)**	**Avg. plotdens (%)**	**Avg. DBH (cm)**	**Avg. height (m)**	**Basal area LB (m^2/hec)**	**Basal area RB (m^2/hec)**	**Most common tree LB**	**Most common tree RB**
Boone	7.84	14.22	84.99	87.17	31.56	9.57	28.34	19.27	Silver maple	Boxelder
Clear	14.00	180.65	93.93	97.23	22.46	13.27	25.99	19.33	Elm	Elm
Onion	5.00	76.38	96.32	97.44	23.80	10.81	22.48	28.49	Honey locust	Honey locust
Onion2	1.33	13.97	94.74	99.74	19.47	10.54	9.25	21.07	Boxelder	Ash
Paint	2.43	12.50	39.75	35.78	43.41	18.01	39.72	28.82	Boxelder	Boxelder
Southfork	5.68	33.64	70.27	84.92	30.67	11.30	42.29	13.08	Ash	Silver maple
Springbrook	8.75	124.06	63.08	75.91	39.24	14.18	23.94	27.08	Walnut	Boxelder
Walnut	8.57	141.21	86.13	96.53	32.01	15.41	18.17	24.61	Buckeye	Honey locust
Wolf	3.67	27.68	83.84	95.45	30.73	8.60	28.39	39.84	Boxelder	Boxelder

C. Pieces of large wood

In the 10 stream reaches, a total of 321 general LW pieces were counted and measured within zones 1-4 of the channel (Table 11). The average DBH of LW pieces was 20.77 cm and 3.36 m in length. Of these general pieces of LW, 72.8% were parallel to the channel and 27% perpendicular. The decay class of LW varied by stream (Figure 23). The zones in which pieces of LW were found also varied with streams and their drainage areas (Figure 24). The average general LW volume per unit stream area was 40.69 m^3m^{-2} and the average LW abundance per unit stream length was 10.08 m^{-1}.

Table 10: LW data summarized. Total # of pieces contains pieces also found in jams.

Reach	Total # of jams	Total # of pieces	Total LW $100m^{-1}$	Avg. Length (m)	Avg. DBH (cm)
Boone	2	119	32.16	2.99	21.99
Clear	2	53	26.50	4.36	19.50
Holland	0	0	0.00	0.00	0.00
Onion	1	43	14.33	3.55	16.56
Onion 2	1	62	20.67	2.74	17.94
Paint	1	88	23.78	3.62	19.41
South Fork	2	62	16.76	3.52	20.90
Springbrook	3	45	18.75	2.50	20.45
Walnut	2	63	18.00	3.21	23.48
Wolf	2	91	30.33	3.79	21.36

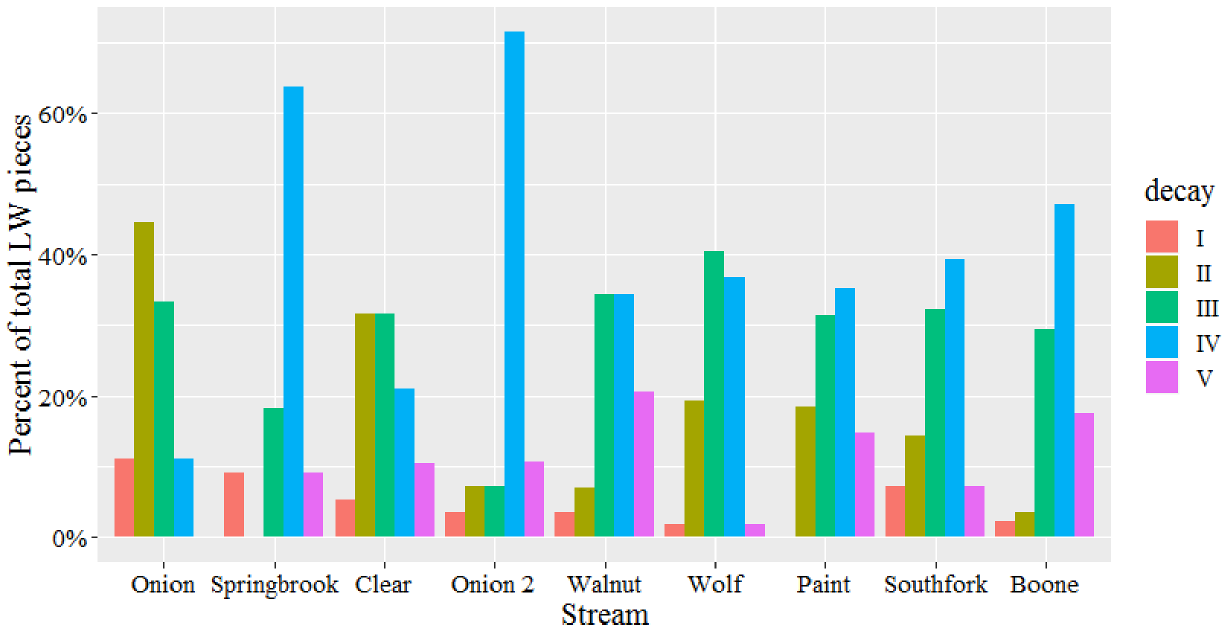

Figure 23: Percent of LW pieces ONLY within decay classes I-V. Holland Creek not included. Streams are ordered by increasing drainage area, km^2. Pieces within jams NOT included.

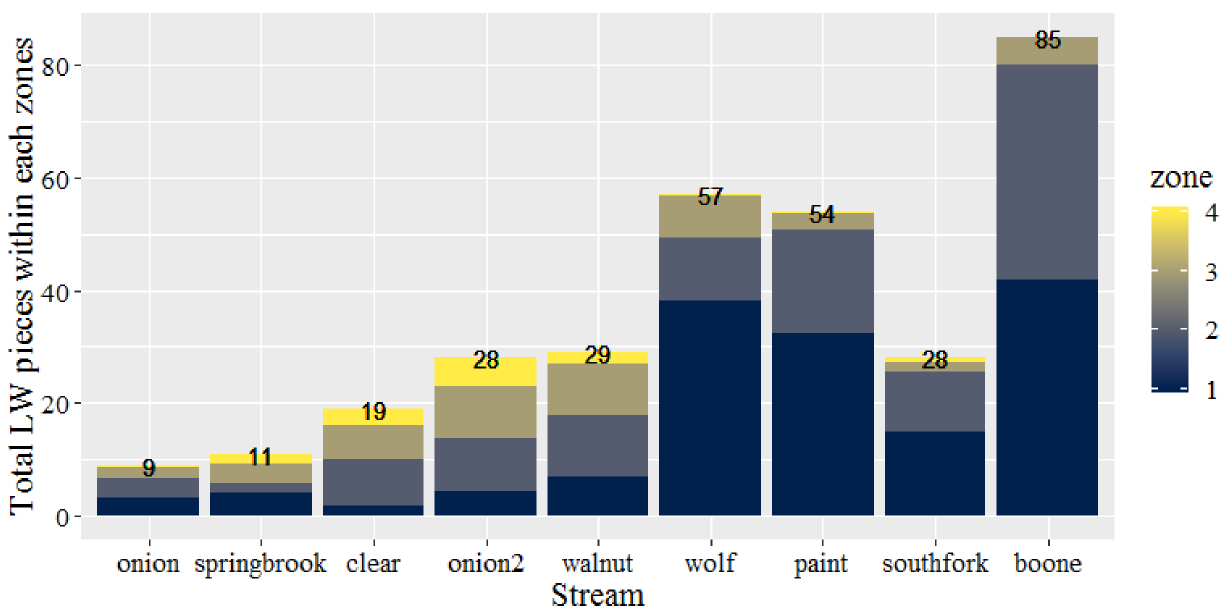

Figure 24: Total LW pieces within channel zones 1-4. Holland Creek not included. Streams ordered by increasing drainage area, km^2. Pieces within jams NOT included. Top number is total LW pieces.

No significant relationships existed between the standard deviation BF width and LW abundance (LWper100m and LWperarea) (Table 12). Similarly, no significant relationships existed between the standard deviation TOB width and LW abundance (LWper100m and LWperarea) (Table 13). Additionally, no significant relationship was found between riparian forestry variables (number of CWD, average height, DBH, basal area, and density) and the abundance of LW (Appendix B).

Table 11: Spearman's non-parametric correlation tests using standard deviation of bank full width as response.

Predictor	Correlation coefficient	*S*	p-val
LW per reach area	-0.2606061	208	0.4697
All LW per 100m	0.5757576	70	0.08777

Table 12: Spearman's non-parametric correlation tests using standard deviation of top of bank width as response.

Predictor	Correlation coefficient	*S*	p-val
LW per reach area	-0.5410359	254.27	0.1063
All LW per 100m	0.1337392	142.93	0.7126

D. Jams

Over the 10 streams, 16 jams were encountered and an average of 0.550 jams per 100 m. Within the jam, the average number of qualifying pieces in all zones was 19 pieces per reach (Figure 25). A majority of the qualifying pieces were found in zone 1 and zone 2 and were within the 1.5-5 m and 10-30 cm range. Most of the jams encountered were channel-spanning dam jams (81%). All jam variables are summarized in Appendix B.

The results of the GLM with fixed effects for width (TOB and BF) and presence of jams did not yield any significant results, however, all models did predict higher least square means for cross-sections with jams (Table 14).

Within jams, 36% of the 10 streams contained 2 key pieces. The average diameter of the key piece was 36.93 cm and 10.77 m in length. 72% of the key pieces still had their roots intact.

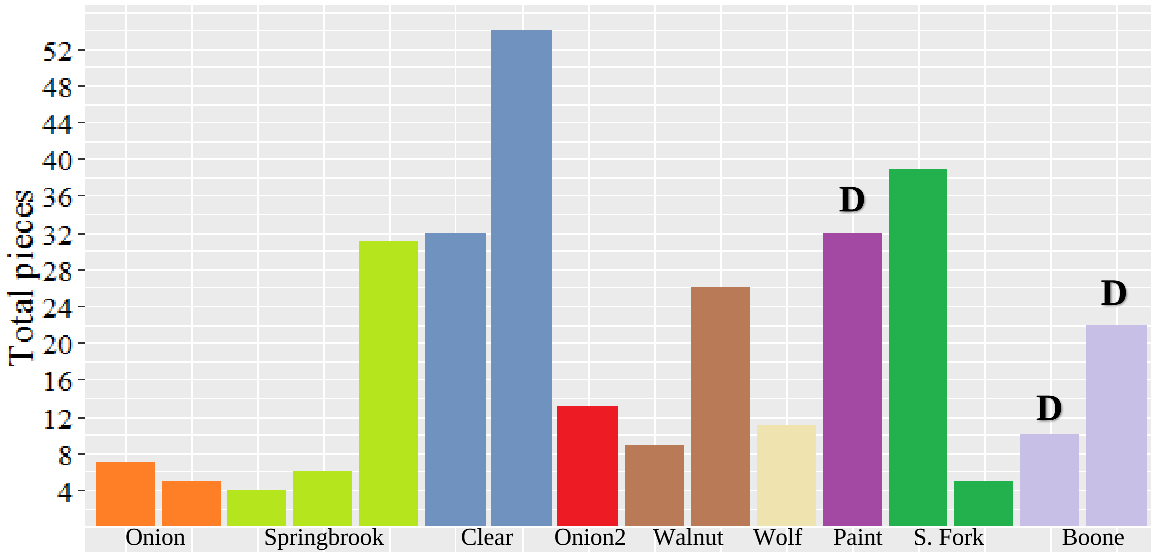

Figure 25: Bar chart of total number of qualifying pieces per each jam found on field streams. "D" above bar indicates deflector jam. All other jams were channel spanning dams. Holland not included.

Table 13: Results of jams as a predictor of channel width. Response column also indicates method width was normalized.

Response variable	**"Yes" L.S.M**	**Difference in L.S.Ms**	***p*-val**
Field hydraulic geometry TOB width (m)	1.0540	-0.04532	0.4852
Average TOB width (m)	1.0224	-0.02932	0.5448
Field hydraulic geometry BF width (m)	1.0970	-0.08376	0.1728
Average BF width (m)	1.0443	-0.08253	0.1417

CHAPTER 4: DISCUSSION

In this study, I developed a method to use LiDAR data to address the relationship of riparian vegetation and top of channel width at the watershed scale as well as at a regional state scale. The analysis to investigate if forested streams are wider in Iowa indicated that as streams widen, the probability of the riparian vegetation being forested increased. This study, unlike others before it, encompassed 21 watersheds with drainage areas of 2 km^2 to over 4000 km^2 and with channels ranging from 2 m to 98 m in width. Variables such as basin slope and geology may have some influence on these results, but by including watersheds from various landforms, which vary in geology, slope, dominant bed material size and hydrological regime, these conclusions are robust and can be applied to the state of Iowa.

Extensive field work allowed for measurements and observations of the morphological impact of LW in Iowa for the first time. Perhaps because we had limited amounts of field sites or our range of stream sizes was relatively small, we were unable to detect strong relationships between stream width, LW, jams, and riparian variables. However, there are indications from field data and observations of LW and jam abundance, volume, diameter, and length that these things reflect one another as well as geomorphic, hydrologic, and riparian forest factors in Iowa streams, as they do all around the world (Swanson 2003).

4.1 Geospatial

While the results of the regional downstream hydraulic geometry analysis indicate strong relationships of width and depth with upstream contributing area, the relationship may have been stronger with the inclusion of smaller streams (< 15 km^2). The abundance of small headwater streams in the dataset from which channel widths were drawn was limited as the Iowa DNR only digitized the top of banks for streams wider than 7 m. In principle, this is a simple problem to solve by devoting more time to digitizing narrow stream channels, but this was beyond the scope of my study. It must also be mentioned that hand digitizing is very subjective and can lead to miscalculations in channel width with inclusion of certain geomorphic features in the stream such as point bars or channel meanders. Future studies should strive to create structured guidelines for channel bank digitization as well as maintain the same digitizer for the entire process.

We also did not include seven streams in our DHG regional curve due to their anomalously high α values as well as negative β values. These inconsistencies in the data could be due to human error, but also could be from downstream stream sections being straightened. Iowa is the most heavily modified landscape in the continental United States and many streams in the state have been straightened to some degree at some point in time (Runkel and Roosa 2015). For this reason, we used the statewide DHG power law and not each stream's individual DHG power law. We did not find any obvious differences between individual DHG curves and coefficients when taking general geology, soils, or slopes into consideration.

In comparison to empirically-derived regional downstream hydraulic geometry equations for the Midwest, our derived regional DHG curve implied a faster rate of increasing width with increasing drainage area, but an overall smaller predicted channel width (2.74) compared to the α value (3.26) Faustini *et al.* computed from the Temperate Plains ecoregion (2009). Conversely, our β (0.4067) and R^2 (0.6851) were higher than the values computed by Faustini *et al.* (β=0.22, R^2=0.4) for the Temperate Plains ecoregion (2009). Many of our streams are in the midst of channel geometry changes consistent with CEM; therefore, width in some cases can be enhanced in reaches experiencing advanced CEM stages, and this could account for some of the observed deviation (Simon 1989).

Since landscape changes occur over a longer period than human timescales and we cannot observe the evolution of our streams, we invoked ergodicity and have substituted observations in space for observations in time. Space is commonly used as a surrogate for time in geomorphology and ergodicity is often referred to as a “space-for-time” assumption (Micallef *et al.* 2014). By making comparison of streams in different conditions, we can make inferences of long-term stream development. Although our geospatial results are static and only a snapshot in time, the logistic regression analyses using both methods of width normalization indicated that wider stream channels studied in Iowa have a higher probability of being forested. In general, our logistic regression results suggest that with a one meter increase in residual width, the relative odds of forest increases by 4.34%. Although we cannot address specific vegetation mechanisms causing the widening from our GIS data, these results mirror those of Trimble 1997 and disagree with Hey and Thorne 1986.

One possible channel-vegetation interaction that could explain our results is the shading of banks caused by a closed canopy. Results from the logistic regressions run when both sides were forested resulted in a significant and positive relationship. If both banks are forested, it could be expected that they could create a closed canopy on a small-medium stream. As banks are shaded by a dense forest canopy, the lack of sunlight limits the amount of grass which can grow on the banks. With little to no grass, fine sediment will not be trapped, no deposition will ensue, and the accretion which leads to channel narrowing will be slowed or not occur. (Davies-Colley 1997, Trimble 1997). The result of a dense forest canopy is the inability of the channel to counteract and wood-related widening by adequate deposition. A similar process could be occurring on streams only forested on one bank.

Stream size-dependent impacts could also be affecting the patterns between width and the riparian vegetation. When watersheds were separated into groups depending on their drainage areas (following Anderson *et al.* 2004) and logistic regressions were run, results were not significant. This could possibly suggest that the vegetation effect is similar regardless of scale, a result also found by Moody and Troutman 2002.

Although nothing statistically significant was found in our data, species of riparian tree could potentially impact erosions rates due to specific species characterizations (Simon and Hupp 1987). Different types of tree species provide higher root densities and depths than others (Wynn *et al.* 2004). Canopy shading (discussed previously) can also be impacted by the species of tree impacting the undergrowth and understory. The predicted lifespan of a species is also important as longer-lived trees will grow roots parallel to banks as well as contribute to bank stability for a longer period of time (Melchior 2019).

4.2 Field

Although statistical results do not necessarily indicate that channel widths are significantly different from the presence of LW jams, models do predict higher least square means for reaches with LW jams as well as positive slopes for their regressions. The jam abundance was negatively associated with top of bank channel width, which suggests that stream width affected jam creation and stability suggested by Gurnell *et al*. 2002. However, top of bank width did not affect pieces of LW pieces in the stream. In these wider channels, LW pieces were found along the banks and margins closer to the riparian zone where a greater volume of wood would be introduced as wood in the thalweg of the channel is likely mobile (Gurnell *et al.* 2002).

LW was not statistically related to pool or sediment storage frequency, although 23% and 43% of general pieces created pools and stored sediment, respectively. It has been reported that pool formation by LW was less common in low-gradient streams than in moderate-gradient streams, likely due to differences in stream power (Beechie and Sibley 1997). Our value for sediment storage was higher than other studies (May and Gresswell 2003, Magilligan *et al.* 2008).

Our average abundance of LW pieces (20.13 100 m^{-1}) is lower than the reported LW abundance from the Upper Midwest; defined as Minnesota and Michigan (32.6 100 m^{-1}), but is comparable to other studies in North America ranging from 12.8 to 45.9 100 m^{-1} (Cordova *et al.* 2007). Our piece volume (0.28 m^3 100 m^{-2}) was considerably lower than the Upper Midwest (0.77 m^3 100 m^{-2}) and other locations around the United States ranging from 1.64 to 6.86 m^3 100 m^{-2} (Cordova *et al.* 2007). These differences could be due to forest composition (coniferous vs. deciduous) as well as the disturbances within the regions, channel shape, and stream width (Cordova *et al.* 2007).

The average diameter of our LW (0.21 m) is comparatively small as Cordova *et al*. reported wood exceeding 0.3 m in diameter common in streams of the Pacific Northwest and often is used as a minimum instead of 0.1 m (2007). Our riparian forestry averages were 0.27 m in diameter and 11.2 m in height signifying the ability of riparian wood to be recruited as qualifying LW. Others have found their LW values smaller than expected due to historical perturbations to the riparian vegetation, like logging (Magilligan *et al.* 2008). While Iowa does have a history of logging in bottom land forests, this legacy does not seem to be affecting the riparian areas of our field sites and the ability to recruit and create log jams. Although our piece volume was lower than other regions, Iowa's LW did have the appropriate size and geometry to create stable jams with scour pools and sediment storage. We cannot speak to the storage time of Iowa jams, but perhaps future research could investigate the storage and redistribution of jams.

While many riparian variables were recorded over the field season, if riparian vegetation data was collected on each bank at each cross-section measured, a correlation may have been evident with channel width as certain species of riparian trees can potentially impact erosion or deposition rates due to specific species characterizations (Simon and Hupp 1987, Pizzuto and Meckelnburg 1989). Our most common tree, the boxelder, is referred to as a “trash tree” in the Midwest by many as it grows quickly, has limbs that are brittle and break easily, its trunk is susceptible to rot, and its potential for erosion control is low to medium (Mędrzycki 2011). This tree is often reported within the forest of studies investigating the impact of LW on channel morphology (Trimble 1997, Curran 2009). Perhaps with more riparian data collected, we would have seen a relationship with tree species (specifically boxelder) and channel width, amount of LW, or number of jams.

4.3 Implications

The inspiration for this project stemmed from the results from Trimble 1997 as it is the most widely cited paper from within the Midwest. While Trimble found that his two forested reaches were wider than his two grassy reaches and stated that sediment storage would be decreased, Trimble does not fully explain how this increase in sediment flux would impact cross-sectional area. Also, Trimble’s use of base flow width instead of bankfull or top of bank width is problematic as base flow width can vary through time as bedload storage changes. It was also very difficult to find information on Trimble’s methodology, specifically how long Trimble’s reaches were (Table 2). With all these considerations, Trimble goes on to state that there is limited evidence to suggest that riparian forests converted to grass would allow for the storage of sediment and that his finding should be considered in stream bank restoration projects and plans (Trimble 1997, Melchior 2019). In my GIS analysis of Trimble’s downstream section of Coon Creek, not only were our results insignificant, the probability of the logistic regressions changed from positive to negative when a single land use type (woody wetlands 90) was excluded from the NLCD. I believe the fact that our results were inconclusive on Coon Creek further exposes Trimble's study and results.

Both riparian grass and forest have benefits for bank erosion and as reviewed previously, Trimble is not alone in making broad generalizations about grassed and forested riparian areas. There are many variables and mechanisms that would determine the actual outcome of a stream's resulting width; especially in the modified landscape of Iowa. As only 4% of Iowa's landscape still displays its native characteristics, there are many possible influences from modifications that could have affected my study (Runkel and Roosa 2015). Some questions we could ask are: could channelization to a smaller channel mean that our study isn't accurately measuring stream width? Do the extensive agricultural tile drains cause greater stream flow than what Iowa streams evolved in? Have floods increased historically and would that increase channel width? These questions may beyond the scope of my study, but they are important to Iowa stream restoration where the structure and function of streams in predisturbed conditions are sought (Yochum 2018).

With deeply incised channels, as well unstable banks in many regions of the state (CEM IV), bank stability is a dynamic component to erosion which is driven by flow discharge and sediment load and largely influenced by slope and bank height, but also by subaerial weathering processes (Schumm *et al*. 1984, Beck *et al.* 2018). In the Midwest, the benefit of woody riparian buffers on stabilizing banks, reducing soil loss, and improving water quality has been well documented (Osborne and Kovacic 1993, Schultz *et al*. 2004, Dosskey *et al.* 2010). In order to be more comprehensive, our geospatial analysis could benefit from inclusion of more variables such as riparian vegetation species, basin slopes, annual precipitation amounts, radius of curvature and sinuosity, sediment types, and sediment storage volumes (Anderson *et al*. 2004, Faustini *et al.* 2009).

As we did not find any conclusive evidence for the mechanisms driving forested channels to *actively* widen in Iowa, we cannot support Trimble's results of transient sediment flux and widening to continue past a stream's initial conversion from grass to forest. Although we do not have sediment data, a wider forested stream does not necessarily mean that it's contributing more sediment. To evaluate if forested channels are *actually* contributing more sediment because they are wider, an Iowa focused study would be necessary. By measuring sediment fluxes from grassed and forested streams, we could have a better idea of what we can expect in Iowa if land use conversions take place and evaluate our policies and BPMs.

Due of the success of already established riparian buffers in Iowa, it is evident that blanket generalizations about riparian vegetation are not appropriate. As reviewed previously, in countless studies, forest and grass have been shown to improve channel stability and play a pertinent role in channel morphology. I believe the current polarization of the topic is imprudent and misguided. Along with the many physical stream variables such as sediment supply, magnitude and frequency of the discharge, the characteristics of the bed and bank material, and the riparian vegetation and the potential flow obstructions like LW, we must also take into account historical changes to stream systems, what is reasonable from a process perspective, and what is manageable from a monetary and land-owner perspective during stream restoration projects (Montgomery 1997). As well as the need for more research on this topic, we believe river managers should consider riparian vegetation types on a site-by-site basis taking several factors into consideration to ultimately determine which riparian vegetation type is likely to be most effective in their specific rehabilitation or habitat goal.

CHAPTER 5: CONCLUSIONS

Our results apply to highly degraded lower-gradient sand and gravel-bottom streams across the state of Iowa. An analysis utilizing aerial LiDAR illustrated a higher probability of forested riparian areas as normalized width values increased. This methodology could potentially be used any place where LiDAR products are available and is easily run in an ArcMap model. We also studied forested and nonforested reaches onsite in an attempt to explain the hydraulic mechanisms at work to cause channel widening. We could not reject our null hypothesis that there is a difference between cross-sections with dam jams and without, but we were the first study to collect exciting preliminary information on the LW in Iowa streams. Although only field 10 sites were visited in a state with less than 9% forest, we observed several dam jams with sediment storage, scour pools, and enhancing in-stream habitat. We hope the results of this study can educate the public as well as river managers on riparian vegetation types and stop ambiguous and ill-informed comparisons of riparian grass and forests as well as any resentment towards LW. For future research, following studies from the east and west coast, there are plenty of questions which need to be answered in Iowa and the Midwest pertaining to LW. We believe the most important questions at this time are the impact LW has on in-stream nutrient cycling, creation of habitat for invertebrates and fish, and to quantify LW sediment and nutrient storage.

CITATIONS

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APPENDIX A: METHODS
A1 GIS Flowchart

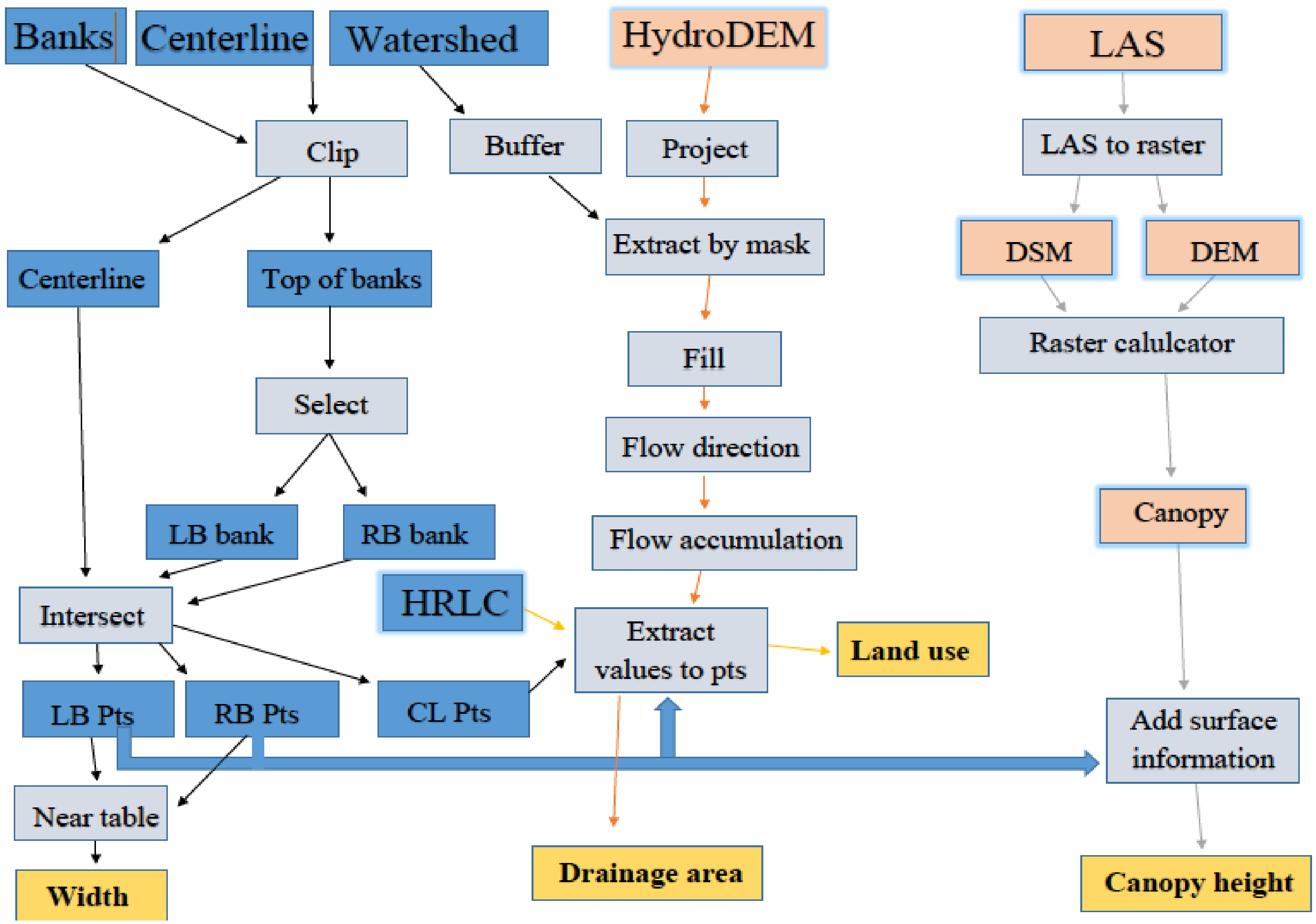

Figure A-1: Flowchart of GIS methods. Dark blue represents vector inputs, pink with blue outline represents raster inputs, light blue represents tools used, and yellow are result outputs.

A2 Model Code

I. SAS Code for logistic regression

```
ods rtf file='U:\FinalData_SAS\State_gradewinners.rtf'; #PDF output
proc glimmix data=Work.State; #dictating process and data
	class gradewinner watershed trans; #categorical variables
	model gradewinner = res / dist = binary ddfm=kenwardroger solution; #logit equation
	random trans / subject=watershed type=sp(pow)(trans) residual; #random effects
run;
ods rtf close;
```

II. SAS Code for channel width and dam jams

```
ods rtf file='U:\FinalData_SAS\damjams_widthcompare.rtf'; #PDF output
proc glimmix data=Work.widthcompare; #dictating process and data
	class watershed station; #categorical variables
	model gradewinner = width / ddfm=kenwardroger solution; #GLMM equation
	random station / subject=watershed type=sp(pow)(trans) residual; #random effects
run;
ods rtf close;
```

III. R code for channel width, LW, and riparian vegetation variables GLMs

Nonparametric:

```
cor.test(LWsummary$stdbf, LWsummary$lw.area, method = "spearman",
      continuity = FALSE,
      conf.level = 0.95)
```

Parametric:

```
glm(avgbankdens~jams.100m, family=gaussian, data=all)
```

APPENDIX B: DATA TABLES
B1 Riparian Forestry for Field Sites

Table B-1: Riparian variables collected within each bank plot

Bank	Stream	Total CWD	Av. bank density	Av. plot density	Av. DBH, cm	Av. height, m	Most common species	# of species	% dead
LB	Boone	28	88.65	90.64	32.91	11.91	S.Maple	5	0
RB	Boone	1	81.33	83.71	30.21	7.23	B.Elder	2	25
LB	Clear	7	92.37	96.88	24.15	13.17	Elm	2	15
RB	Clear	21	95.49	97.57	20.76	13.37	Elm	6	12
LB	Onion	12	98.87	95.67	21.57	9.79	H.Locust	2	14
RB	Onion	3	93.76	99.22	26.02	11.84	H.Locust	7	4
LB	Paint	2	56.84	52.68	39.22	18.73	B.elder	4	0
RB	Paint	7	22.65	18.88	47.60	17.29	B.elder	1	0
LB	S. Fork	13	91.59	96.10	34.03	13.05	Ash	7	4
RB	S. Fork	8	48.95	73.74	27.32	9.54	S. Maple	4	40
LB	Sprbrook	9	50.43	65.33	44.06	14.23	Walnut	2	12
RB	Sprbrook	12	75.73	86.48	34.42	14.13	B.elder	2	8
LB	Walnut	10	73.65	96.53	36.36	16.93	H.Locust	6	0
RB	Walnut	20	98.61	96.53	27.66	13.88	Buckthorn	5	0
LB	Wolf	7	82.93	99.31	30.69	9.83	B.elder	6	11
RB	Wolf	4	84.75	91.59	30.76	7.36	B.elder	4	7
LB	Onion2	2	98.70	99.48	15.14	9.15	B.elder	7	0
RB	Onion2	2	90.77	100.00	23.80	11.93	Ash	6	0

B2 LW Variables for Field Sites

Table B-2: All LW variables for field sites. Roman numerals represent decay class. Z1-Z4 represent zones

Stream	LW/ 100m	All ≥ 10cm	All ≥ 20cm	All ≥ 50cm	% Perp	% Para	% I	% II	% III	% IV	% V	% POOL	% SED	% Z1	% Z2	% Z3	% Z4
Boone	22.97	85	39	5	21	79	2	4	29	47	18	21	59	49%	45%	6%	0%
Clear	9.5	19	7	0	32	68	5	32	32	21	11	11	32	9%	45%	31%	15%
Onion	3	9	2	0	33	67	11	44	33	11	0	33	56	35%	38%	23%	5%
Onion2	9.33	28	8	0	18	82	4	7	7	71	11	11	36	15%	34%	33%	18%
Paint	14.59	54	19	1	22	78	0	19	31	35	15	13	26	60%	34%	5%	1%
S.fork	7.57	28	16	0	57	43	7	14	32	39	7	N/A	N/A	53%	38%	6%	3%
Walnut	8.29	29	16	0	31	69	3	7	34	34	21	7	34	24%	37%	32%	7%
Wolf	19	57	29	0	26	74	2	19	40	37	2	19	33	67%	20%	13%	1%

B3 GLM and Correlation Result Tables

Table B-3: Spearman's non-parametric correlation tests using field.tob as response variable

Predictor	**Correlation coefficient**	***S***	***p*-val**
LW area	-0.6242	268	0.0603
CWD per area	-0.5030	248	0.1434
All LW per 100m	0.3576	106	0.3128
Jams per 100m	-0.2500	206.25	0.4860
BF depth SD	-0.0303	170	0.9457
Avg. bank dens.	-0.4667	242	0.1782
Avg. plot dens.	-0.4667	242	0.1782
Avg. DBH	0.2364	126	0.5139
Avg. height	-0.1879	196	0.6076
Basal LB	0.5636	72	0.0958
Basal RB	-0.2727	210	0.4483

Table B-4: Spearman's non-parametric correlation tests using standard deviation of bank full as response

Predictor	**Correlation coefficient**	***S***	***p*-val**
LW per reach area	-0.2606	208	0.4697
CWD per area	-0.2121	200	0.5599
CWD per 100m	0.5758	144	0.7329
All LW per 100m	0.5758	70	0.0877
Jams per 100m	0.0243	107	0.9467
BF depth SD	-0.0788	178	0.8380
Avg. bank dens.	-0.4909	246	0.1544
Avg. plot dens.	-0.5152	250	0.1328
Avg. DBH	0.3455	108	0.3305
Avg. height	0.1394	142	0.7072
Basal LB	0.7091	48	0.0275
Basal RB	-0.1272	186	0.7329

Table B-5: Spearman's non-parametric correlation tests using average bank density as response

Predictor	**Correlation coefficient**	***S***	***p*-val**
LW per reach area	0.4545	90	0.1909
CWD per area	0.4787	86	0.1661
CWD per 100m	0.2606	122	0.4697
All LW per 100m	0.7329	144	0.7329
Jams per 100m	0.1829	135	0.613

Table B-6: Pearson correlation matrix of all normal field variables

	lwvol/ reach	lwvol/ area	allLW/ 100m	jams/ 100m	jams/ area	lw/ area	cwd/ 100m	cwd/ area	Avg dbh	Avg height	basal. lb	basal. rb	height. lb	height. rb
lwvol/ reach	1.00	0.78	0.47	0.62	0.45	0.22	0.47	0.28	0.82	0.61	0.57	0.46	0.64	0.52
lwvol/ area	0.78	1.00	0.36	0.72	0.55	0.17	0.44	0.27	0.72	0.58	0.56	0.20	0.63	0.45
allLW/ 100m	0.47	0.36	1.00	0.47	0.14	0.35	0.44	0.12	0.64	0.51	0.57	0.66	0.59	0.44
jams/ 100m	0.62	0.72	0.47	1.00	0.89	0.67	0.79	0.72	0.50	0.46	0.32	0.39	0.41	0.44
jams/ area	0.45	0.55	0.14	0.89	1.00	0.80	0.72	0.87	0.32	0.45	0.04	0.31	0.30	0.51
lw/ area	0.22	0.17	0.35	0.67	0.80	1.00	0.63	0.83	0.31	0.57	0.05	0.57	0.38	0.70
cwd/ 100m	0.47	0.44	0.44	0.79	0.72	0.63	1.00	0.86	0.33	0.46	0.31	0.15	0.45	0.44
cwd/ area	0.28	0.27	0.12	0.72	0.87	0.83	0.86	1.00	0.19	0.47	0.04	0.19	0.33	0.55
Avg dbh	0.82	0.72	0.64	0.50	0.32	0.31	0.33	0.19	1.00	0.86	0.79	0.69	0.90	0.75
Avg height	0.61	0.58	0.51	0.46	0.45	0.57	0.46	0.47	0.86	1.00	0.63	0.58	0.96	0.97
basal. lb	0.57	0.56	0.57	0.32	0.04	0.05	0.31	0.04	0.79	0.63	1.00	0.43	0.78	0.44
basal. rb	0.46	0.20	0.66	0.39	0.31	0.57	0.15	0.19	0.69	0.58	0.43	1.00	0.53	0.61
height. lb	0.64	0.63	0.59	0.41	0.30	0.38	0.45	0.33	0.90	0.96	0.78	0.53	1.00	0.86
height. rb	0.52	0.45	0.44	0.44	0.51	0.70	0.44	0.55	0.75	0.97	0.44	0.61	0.86	1.00

Table B-7: P-values of Pearson correlations from Table 16

	lwvol/ reach	lwvol/ area	allLW/ 100m	jams/ 100m	jams/ area	lw/ area	cwd/ 100m	cwd/ area	Avg dbh	Avg height	basal. lb	basal. rb	height. lb	height. rb
lwvol/ reach	1.00	0.01	0.17	0.06	0.19	0.53	0.17	0.43	0.00	0.06	0.08	0.18	0.05	0.13
lwvol/ area	0.01	1.00	0.31	0.02	0.10	0.63	0.20	0.45	0.02	0.08	0.09	0.57	0.05	0.20
allLW/ 100m	0.17	0.31	1.00	0.17	0.69	0.32	0.20	0.74	0.04	0.13	0.08	0.04	0.07	0.20
jams/ 100m	0.06	0.02	0.17	1.00	0.00	0.03	0.01	0.02	0.14	0.18	0.36	0.26	0.24	0.20
jams/ area	0.19	0.10	0.69	0.00	1.00	0.01	0.02	0.00	0.36	0.20	0.91	0.39	0.40	0.13
lw/ area	0.53	0.63	0.32	0.03	0.01	1.00	0.05	0.00	0.38	0.09	0.88	0.09	0.27	0.02
cwd/ 100m	0.17	0.20	0.20	0.01	0.02	0.05	1.00	0.00	0.35	0.18	0.38	0.67	0.19	0.20
cwd/ area	0.43	0.45	0.74	0.02	0.00	0.00	0.00	1.00	0.59	0.17	0.91	0.61	0.35	0.10
Avg dbh	0.00	0.02	0.04	0.14	0.36	0.38	0.35	0.59	1.00	0.00	0.01	0.03	0.00	0.01
Avg height	0.06	0.08	0.13	0.18	0.20	0.09	0.18	0.17	0.00	1.00	0.05	0.08	0.00	0.00
basal. lb	0.08	0.09	0.08	0.36	0.91	0.88	0.38	0.91	0.01	0.05	1.00	0.22	0.01	0.21
basal. rb	0.18	0.57	0.04	0.26	0.39	0.09	0.67	0.61	0.03	0.08	0.22	1.00	0.12	0.06
height. lb	0.05	0.05	0.07	0.24	0.40	0.27	0.19	0.35	0.00	0.00	0.01	0.12	1.00	0.00
height. rb	0.13	0.20	0.20	0.20	0.13	0.02	0.20	0.10	0.01	0.00	0.21	0.06	0.00	1.00

B4 Jam Variable Data for Field Sites

Table B-8: Key piece and Jam variables for all field sites (excluding Holland). Z1-Z4 represents the length of key piece in zones 1-4.

Stream	Jam	Orientation	Diam., cm	Z1, m	Z2, m	Z3, m	Z4, m	Total length, m	Decay class	Log, RW, Both	Position
Boone	1	PERP	16.6	7	4	0	0	11	II	Both	RB
Boone	2	PAR	43	15.3	0	0	0	15.3	III	Both	RB
Clear	1	PERP	38	0	8	1	2.5	11.5	III-IV	Both	Spanning
Clear	1	PAR	22.5	5.2	3.9	2.2	1.5	12.8	III	Both	LB
Clear	1	PAR	33	1.8	5.8	3.4	2.2	13.2	III-IV	Both	RB
Clear	2	PERP	32	2	9.1	2.4	0	13.5	III	Both	Spanning
Onion	1	PAR	56.7	4.24	0	0	0	4.24	III-IV	Log	LB
Onion	1	PERP	21	0	5.3	8.65	0	13.95	IV	Log	LB
Onion 2	1	PERP	36	0	10.5	0	0	10.5	II	Both	RB
Paint	1	PAR	84	0	6.8	0	0	6.8	III	Both	RB
S.Fork	1	PERP	40	11	0	0	0	11	IV	Log	Spanning
S. Fork	1	PERP	28	3	4	0	0	7	III	Both	RB
S.Fork	2	PAR	58	6.4	0	0	0	6.4	V	Log	Spanning
S.Fork	2	PERP	25	0	6.6	0	0	6.6	V	Both	LB
S.Fork	2	PAR	26	15	0	0	0	15	II	Both	Spanning
Sprbrook	1	PAR	24.8	0	0	2.8	8.7	11.5	III	Both	LB
Sprbrook	2	PERP	23	7.1	0	0	0	7.1	III	Both	Spanning
Sprbrook	3	PERP	25.8	3	5.2	0	0	8.17	II	Both	Spanning
Walnut	2	PERP	37	0	4.7	6.5	2.1	13.3	III	Both	Spanning
Walnut	2	PAR	54	0	4.8	5	4	13.8	IV	Both	LB
Wolf	1	PERP	40	5.5	9.5	0	0	15	I	Both	Spanning
Wolf	2	PERP	48	0	9.2	0	0	9.2	II	Log	Spanning